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TRIASSIC-JURASSIC CENOCERATIDS FROM NEW ZEALAND

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Summary

Evolution of nautiloids during the Triassic is a culmination of trends established in the late Paleozoic. In the late Triassic, the group suffered almost complete extinction. In New Zealand, the meagre fossil nautiloid fauna is extremely important because it includes representatives of the stock which survived into the Jurassic.

Cenoceras trechmanni (Kummel) from the Otamitan Stage (upper Carnian) is redescribed and figured. Lower Jurassic nautiloids, recorded for the first time in New Zealand, are represented by two indeterminate species of *Cenoceras* from the Aratauran Stage (Lower Lias) of Southland.

Striking features of the evolutionary history of ammonoids and nautiloids are the several periods of near extinction experienced by both groups. In the ammonoids, these times of crisis came at the close of the Permian and at the close of the Triassic, and the final extinction of the group was at the close of the Cretaceous. The nautiloids had a somewhat similar history. This group had been declining ever since the Silurian, but the first, almost cataclysmic, phase of extinction was not until the Late Triassic; there are, for instance, no Rhaetic nautiloids. There was no significant change in evolutionary development of the nautiloids at the Permian-Triassic boundary such as is so well marked in the history of the ammonoids. In fact, the evolution of Triassic nautiloids is essentially merely a culmination of trends and patterns established in the late Paleozoic. The phase of extinction of the group in the latest Triassic was nearly complete, except for a single surviving stock from which sprang a new adaptive radiation to populate Jurassic and Cretaceous seas.

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The fossil nautiloid record for New Zealand, though very imperfect, is extremely important, for among the known species it is considered that there are representatives of the stock which survived from the Triassic into the Jurassic. The Upper Triassic nautiloid fauna consists of an orthoceratoid, *Proclydonautilus mandevillei* (Marshall), *Proclydonautilus* sp. (*fide* Marwick, 1953, p. 77), and *Cenoceras trechmanni* (Kummel, 1953a, 1956). Lower Jurassic nautiloids from New Zealand are recorded and described in this paper for the first time. These are indeterminate species of the genus *Cenoceras*. It is these specimens of Late Triassic and Early Jurassic *Cenoceras* which are of particular interest, and are described here.

For a proper perspective of the position of *Cenoceras* in the evolution of Mesozoic nautiloids, it is necessary to consider the whole spectrum of Triassic and Jurassic nautiloids. As mentioned above, the evolutionary patterns of Triassic nautiloids can be summarized as those of culminating trends which began in the Carboniferous. Three distinct lines of development are represented (Fig. 1). One includes the Paranautilidae, Clydonautilidae, Siberionautilidae, and Gonionautilidae, characterized by globular, occluded conchs and tendency toward sinuosity of the suture. The second major group consists of the Tainoceratidae, including most of the "ornamented" Triassic nautiloids. This stock includes Pennsylvanian, Permian, and Triassic genera which are generally evolute, and have nodes and ribs. The third major group comprises the Grypoceratidae and Syringonautilidae. The Grypoceratidae include evolute to involute, generally smoth, compressed nautiloids of Pennsylvanian, Permian, and Triassic age, with a tendency for modification of the venter. The Upper Triassic developments of this family, *Grypoceras* and *Gryponautilus*, are quite unlike *Cenoceras trechmanni*. Within the Syringonautilidae there are forms which are very similar in conch pattern to *Cenoceras*—namely, *Syringoceras* and *Syringonautilus*. These two genera include evolute nautiloids with whorl sections rounded in the early volutions, but becoming more quadrate in outline adorally. The outer whorls have distinct umbilical and ventral shoulders and steep umbilical walls. The shell bears fine radial and longitudinal lines. These two genera differ only in the position of the siphuncle; *Syringoceras* has its siphuncle very near but not at the venter; *Syringonautilus* has its siphuncle in a more central position.

The Syringonautilidae also include three aberrant genera of Norian age—namely, *Clymenonautilus*, *Juvavionautilus*, and *Oxynautilus*. *Clymenonautilus* has a conch pattern like that of *Syringonautilus*, but has a very sinuous suture convergent to the type of suture present in the Clydonautilidae. *Juvavionautilus*, in its conch shape, is a heterochronus homeomorph of *Domatoceras* of the Pennsylvanian and Permian. *Oxynautilus* is an involute oxycone similar in its conch pattern to *Stenopoceras* of the Pennsylvanian and Permian.

Early Jurassic nautiloids are a homogenous complex of nearly worldwide extent, quite unlike the heterogenous complex of several distinct evolving lines that characterize the Triassic fauna. Approximately 60 species of Liassic nautiloids have been described to date, showing a

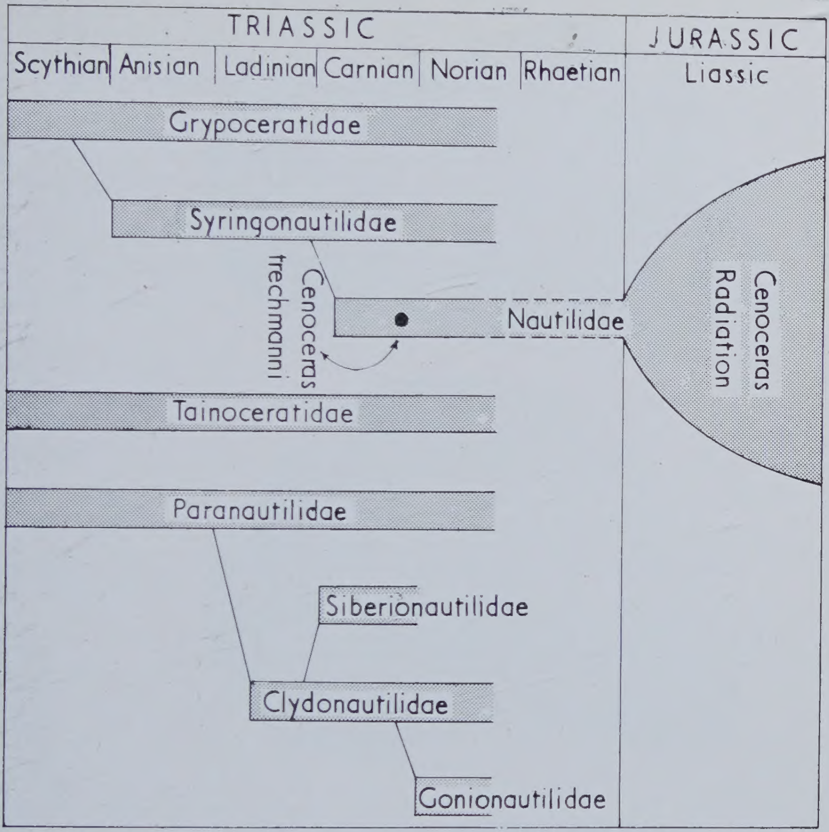
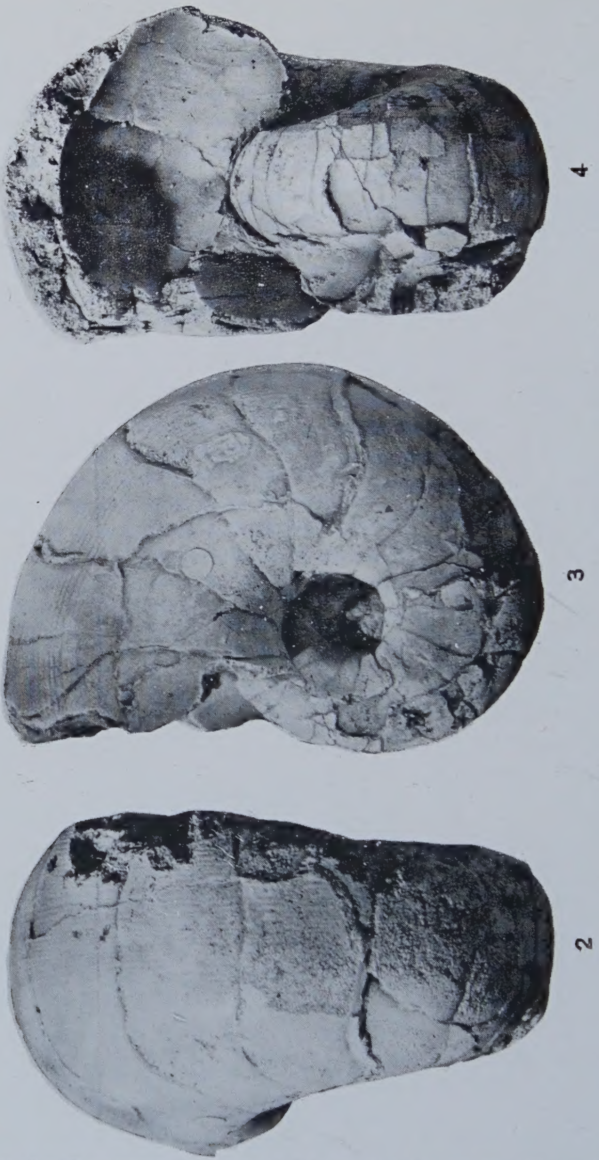


FIG. 1.—Phylogenetic diagram illustrating the relationships of the Liassic cenoceratids with the Triassic nautiloid families.

wide range of variation in conch shape, size, suture, and shell characters. Cross-sections of a large number of Liassic nautiloids can be found in Pia (1914) and Kummel (1956). In spite of the rather great variability in most morphological features, an almost complete series of transitional forms can be recognized. So far as nautiloids are concerned, an ecological vacuum existed at the close of the Triassic after the extinction of the several well-known stocks. When the earliest Jurassic seas again invaded the continents, nautiloid populations consisted largely of members of the surviving stock, such as represented by *Cenoceras trechmanii.* The great variation in morphological characters of Liassic Cenoceratids is a reflection of the extensive adaptive radiation taking place at that time. This was the so-called "plastic" phase in the evolution of the group. Out of this early "plastic" phase arose directly or indirectly the stocks which populated the later Jurassic and Cretaceous seas. It is first in the Middle Jurassic that clearly recognizable phyletic lines can be recognized (e.g., Cymatoceratidae, Pseudaganididae, and Paracenoceratidae) which have their origin within the complex of Liassic nautiloids, though precise details on this relationship are not known as yet.



Figs 2, 3, 4.—*Cenoceras trechmanni* (Kummel). Otamitan (Upper Triassic), Hokonui Hills. Holotype, British Museum (Natural History) (21947) XI.

Genus **Cenoceras** Hyatt, 1883

Cenoceras trechmanni (Kummel). Figs 2–8

1878. *Nautilus mesodicus,* Hector. N.Z. geol. Surv. Rep. Geol. Explor. 1877–8 (11) : X.

1886. *N. mesodicus,* Hector. Outline Geol. N.Z.: 72.

1910. *Grypoceras mesodicum*, Diener in Boehm. Centbl. f. Min. (1910): 635.

1913. *G. mesodiscum* (Hauer), Thomson. N.Z. geol. Surv. Pal. Bull. 1: 36.

1918. *G.* cf. *mesodiscum* Hauer, Trechmann. Quart. J. geol. Soc. 73 (3): 181.

1927. *Nautilus (Grypoceras)* cf. *mesodicus* Hauer, Wilkins. N.Z. geol. Surv. Pal. Bull. 12: 24.

1927. *Grypoceras* cf. *mesodicum (Hauer)*, Spath. India geol. Surv. Mem. (Pal. Indica) n.ser. 9: 23.

1953. *Grypoceras* sp., Marwick. N.Z. geol. Surv. Bull. 21: 77.

1953. *Bisiphytes trechmanni* Kummel. Breviora 21: 5.

1956. *Cenoceras trechmanni* (Kummel). Bull. Mus. Comp. Zool. 114 (7): 349.

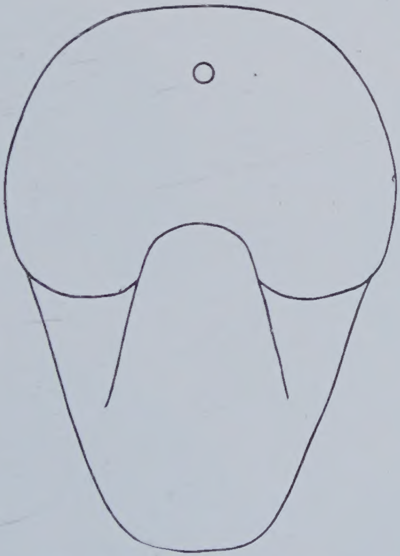
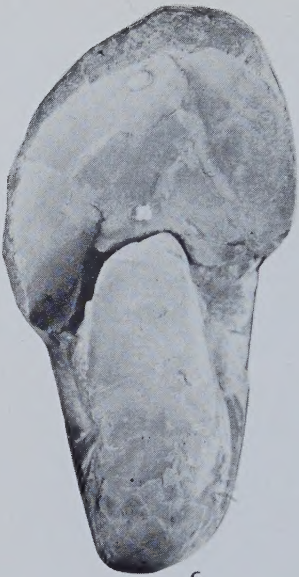


FIG. 5.—Diagrammatic cross-section of *Cenoceras trechmanni*, × 1.

Trechmann's specimen, which forms the type of this species, is a moderately large phragmocone that measures 71 mm in diameter, 38 mm in height of the last whorl, and approximately 50 mm in width of the most adoral part of the last whorl. The conch is evolute, the umbilicus measuring 13·5 mm in diameter. The venter is broadly rounded, as are the ventral shoulders. The whorl sides are somewhat flattened and convergent. The widest part of the whorl is just above the umbilical shoulders, which are more sharply rounded than the ventral shoulders. The umbilical wall is steep and convex.



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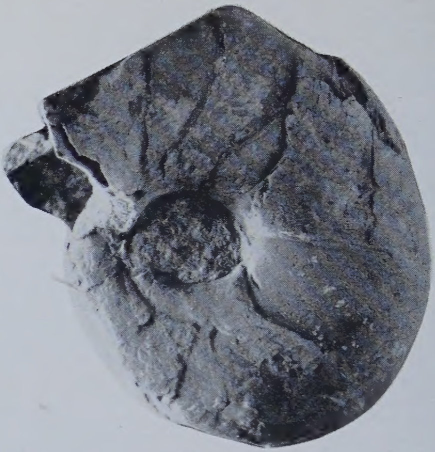

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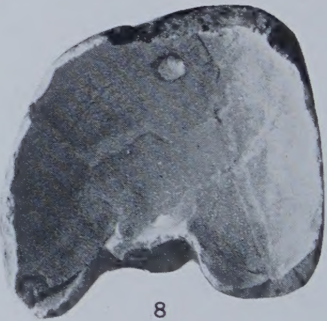

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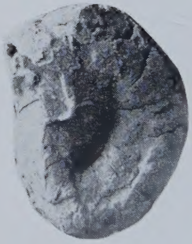

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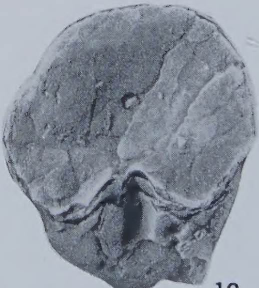

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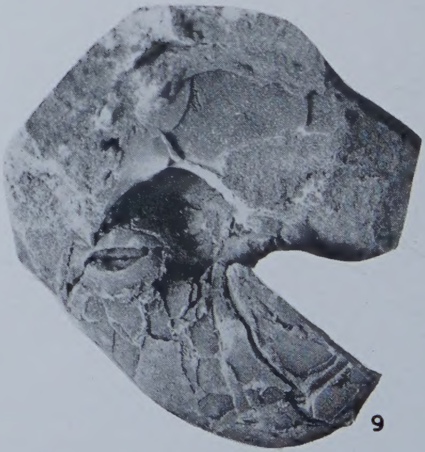

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FIGS 6, 7, 8.—*Cenoceras trechmanni* (Kummel) *Otamitan* (Upper Triassic), Hokonui Hills. Paratype, University of Otago Museum.

FIGS 9, 10.—*Cenoceras* sp.indet. I. North Face, Flag Hill, Southland, GS 6597, CE 1687. Probably *Ectocentrites* Zone, Artauran Stage, Hettangian (L. Lias).

FIG. 11.—*Cenoceras* sp.indet. II. Otamita Valley, west branch of Coneburn, S 169/683, GS 6616, CE 1688. *Psiloceras* Zone. Aratauran Stage, Hettangian (L. Lias).

Only fragmentary portions of the shell are preserved. The conch bears fine strigations both on the whorl sides and the venter of the inner whorls. On the most adoral volution, the strigations are present only on the venter. On this region there are about 7 lines in a width of 5 mm. The suture forms a broad, very shallow ventral lobe and a slightly deeper lateral lobe. There is an annular lobe. The siphuncle is subventral in position, 2 mm in diameter, and lies 7 mm from the venter.

In addition to the type specimen, which is deposited in the British Museum (Natural History), there is available a topotype specimen belonging to the University of Otago Geology Museum labelled "*Grypoceras*" in Marshall's handwriting. This specimen is a slightly crushed phragmocone which measures 81 mm in diameter and agrees in all essential features with the type specimen, though not nearly as well preserved.

It is primarily on the basis of the prominent peripheral strigations that these New Zealand specimens are placed in *Cenoceras* rather than the closely similar *Syringoceras* or *Syringonautilus*. In addition, they show a slightly greater degree of involution, the umbilicus approximating 25 to 30% of the diameter of the conch in *Syringoceras* and *Syringonautilus* but only 19% in *Cenoceras trechmanni*. Among typical Liassic species of *Cenoceras,* the width of the umbilicus ranges from 20% the diameter of the conch to completely occluded, as in *C. simillimus* (Foord and Crick). A trend towards greater involution, common amongst various groups of Triassic nautiloids, is well illustrated in the *Domatoceras-Grypoceras* line in the Grypoceratidae and in the *Metacoceras-Mojvaroceras* line in the Tainoceratidae (Kummel, 1953b).

LOCALITY: Holotype and topotype from Otamitan (Upper Carnian) in the Hokonui Hills. Marwick (1937, p. 77) illustrated a well-preserved specimen of this species from GS 133, Roaring Bay, Nugget Point, and recorded another specimen from GS 437, Nautilus beds, Mt. Heslington. A poorly preserved specimen from the Otamitan (S 159/644) of Taringatura Hills submitted to the author by Mr J. D. Campbell is also most probably of this species.

REPOSITORY: Holotype, British Museum (Natural History) C 21947; topotype, University of Otago Geological Museum.

Cenoceras sp.indet. I. Figs 9–10

A fragmentary specimen from Flag Hill, Southland, can be assigned with confidence to the genus *Cenoceras* even though the specific affinities of the specimens cannot be certainly determined. The conch is rather involute, with a deep, open umbilicus. The whorl-section of the phragmocone shows a broadly rounded venter, arched flanks, and broadly rounded umbilical shoulders. The siphuncle is approximately central in position. At a diameter of roughly 44 mm, the whorl-section measures 27 mm in width and 22 mm in height; the impressed zone is approximately 5·5 mm. The suture includes very shallow lateral and ventral lobes plus an annular lobe. Only a portion of the flanks and umbilical shoulder and wall of the living chamber are preserved. The umbilical wall is broadly arched and nearly vertical to the flanks, which appear to be flattened. There is a distinct change in whorl shape from the phragmocone to the living chamber. No surface markings of any kind can be observed.

The range of variation in conch shape of the numerous species of *Cenoceras* is greater than that in any other genus of Mesozoic nautiloid. The rounded, somewhat depressed whorl-section of the phragmocone and the more quadrate outline of the living chamber are comparable to other Liassic species, such as *Cenoceras quadrangulus* (Pia), *C. jurensis* (Quenstedt), *C. intermedius* (J. Sowerby). Because of the fragmentary nature of this New Zealand specimen, more detailed comparison with other Liassic nautiloids is not possible.

LOCALITY: North Face, Flag Hill, Southland, GS 6597, CE 1687. Probably *Ectocentrites* Zone, Aratauran Stage, Hettangian (L. Lias).

Cenoceras sp.indet. II. Fig. 11

A small phragmocone of one and one-half volutions 27 mm in diameter is worthy of recording, since it is the second of two specimens of Liassic nautiloids known from New Zealand. Unfortunately, this specimen is crushed and poorly preserved, but the general characters of the conch, suture, siphuncle that are visible indicate that it is most certainly a species of *Cenoceras*. Detailed description and comparison with other species is not warranted.

LOCALITY: Otamita Valley, west branch of Coneburn, S 169/683, GS 6616, CE 1688. *Psiloceras* Zone, Aratauran Stage, Hettangian (L. Lias).

REPOSITORY: N.Z. Geological Survey, Lower Hutt.

REFERENCE

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LOWER TRIASSIC AMMONOIDS FROM WESTERN SOUTHLAND, NEW ZEALAND

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Summary

Four species of Lower Triassic (Scythian) ammonoids are recorded from Malakoff Hill, Wairaki Downs, Southland. The assemblage (*Owenites* cf. *O. koeneni, Flemingites* cf. *lidacensis, Subvishnuites welteri,* and *Wyomingites* cf. *aplanatus*) clearly indicates that the fauna belongs to the *Meekoceras* zone (approximately Mid-Scythian). The Lower Triassic (Scythian) formations of the Circum-Pacific Region are reviewed and their ammonoid faunas attributed to the zones and ages of the Scythian Stage.

The extremely thick Triassic strata of New Zealand have not as yet yielded many ammonoids. However, over the past few decades, several small faunas and isolated specimens have been discovered, and various ammonoid zones within the Middle and Upper Triassic are thus now known to be represented. In 1952, Mr A. R. Mutch, of the N.Z. Geological Survey, discovered a small fauna of ammonoids at N.Z. Geol. Surv. fossil locality GS 6585 in a conglomerate bed of Pre-Etalian age which lies above the Lower Permian Productus Creek group along Coal Creek, Malakoff Hill, in the Wairaki Downs (Mutch, 1957). Through the courtesy of Dr C. A. Fleming, of the N.Z. Geological Survey, the author has had the opportunity to study these specimens. Lately, a few additional specimens from the same horizon and locality have been forwarded by Mr J. D. Campbell, of the University of Canterbury, New Zealand. From these two collections, a total of nine specimens has been available for study. Though the material is fragmentary and the preservation leaves much to be desired, species of four genera of Lower Triassic (Scythian) age can be recognized, namely:

Owenites cf. *O. koeneni* Hyatt and Smith
Flemingites cf. *lidacensis* Welter
Subvishnuites welteri Spath
Wyomingites cf. *aplanatus* (White)

This assemblage of genera and species clearly indicates that the fauna belongs to the *Meekoceras* zone, which is approximately mid-Scythian in age. The species present are very similar to congeneric forms in the well-known faunas of the same age from Timor (Welter, 1922) and from western United States in California, Nevada, and Idaho (Smith, 1932). *Owenites* and *Flemingites* are known from both Timor and the western United States; *Wyomingites* is known only from western United States, and *Subvishnuites* is known only from Timor.

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A recently described Lower Triassic fauna from the Kwanto-Mountain region, central Honshu, Japan, most probably also represents the *Meekoceras* zone, and can be considered contemporaneous with the New Zealand fauna and with those from Timor and western United States. This fauna is described by Sagagami (1955), who recognized the following in one horizon:

Ophiceras iwaiense Sakagami
Ophiceras sp.
Vishnuites sp.
Proptychites aff. *rosenkrantzi* Spath
Kingites shimizui Sakagami

Seventeen metres above the horizon with this fauna, Sakagami records an *Aspenites* sp. The genera and species of the lowest fauna represent a mixture of forms not previously recorded as contemporaneous. *Proptychites* generally occurs in horizons above *Ophiceras* and *Vishnuites,* and *Kingites* generally occurs above Proptychites. Such, at least, is the spatial distribution of these genera in classic Lower Triassic localities such as the Salt Range, Himalayas, East Greenland, western North America, etc. The specimens described and illustrated by Sakagami from this horizon are small forms, especially the specimens assigned to *Ophiceras* and *Vishnuites*. Their preservation leaves much to be desired. Dr Sakagami kindly sent the author a few specimens of *Ophiceras iwaiense,* and two forms not included in his report. *O. iwaiense* is not an ophiceratid at all, but clearly a species of *Dieneroceras,* a genus common in the *Meekoceras* zone of western United States. One of the unidentified specimens consists of a half-whorl of body chamber only, but its shape, ornamentation, and degree of involution show it to be a *Juvenites,* another common form in the *Meekoceras* zone of western United States.

Changes in the identification of *Kingites shimizui* and *Proptychites* aff. *rosenkrantzi* are warranted partly because of the above reassignments and partly in support of this revaluation. The shape of the conch and the suture of the specimen named *Kingites shimizui* appear more like those of *Owenites* than of *Kingites*. The acute, sharp-edged venter is quite unlike any species of *Kingites*, but similar features are common in and characteristic of *Owenites*. The Japanese specimen has a very small umbilicus, and typical mature specimens of *Owenites* have larger, funnel-shaped umbilici. However, specimens of *Owenites* from western United States of comparable size to Sakagami's specimen have umbilici of equal dimensions. Finally, the specimen assigned to *Proptychites* aff. *rosenkrantzi* Spath has yielded no suture and is poorly preserved, but could very well be a *Paranannites*.

The single specimen from the upper horizon, *Aspenites* sp., is also poorly preserved and shows no suture, but the general character of the conch as preserved suggests that the generic assignment is justifiable. Sakagami correctly concluded that the horizon with *Aspenites* sp. is of *Meekoceras* zone age, and, if the above conclusions on the affinities of the specimens from the lower horizon are correct, it, too, is of this same age.

A fauna of *Meekoceras* zone age is also known from the Okhotsk-Kolyma Land of eastern Siberia. Popov (1939) has described and illustrated the following species from a Lower Triassic shale in the region of the sources of the Kolyma River:

Pseudosageceras multilobatum Noetling
Ophiceras (Lytophiceras) subleptodiscus Popov
Paranannites globosus Popov
Anahedenstroemia tscherskii Popov

From the data available, these identifications seem correct except that of *Ophiceras (Lytophiceras) subleptodiscus*. The genus *Paranannites* and *Anahedenstroemia* are common in the *Meekoceras* zone of western United States and Timor, as is *Pseudosageceras multilobatum*.

LOWER TRIASSIC (SCYTHIAN) FORMATIONS IN THE CIRCUM-PACIFIC REGION

Over the past two decades, data on the Triassic history of the Circum-Pacific region have been accumulating at an ever-increasing rate, and the discovery of Scythian ammonoids in New Zealand is an event of particular importance. The Lower Triassic deposits and faunas from Timor and western United States have long been known. Southern China has extensive outcrop areas of Lower Triassic rocks, but the record as yet is not entirely clear. Several important contributions on Lower Triassic deposits in Japan, eastern Siberia, and British Columbia have appeared recently, all of which broaden the perspective on this part of the geological column.

As with the remainder of the Mesozoic, Lower Triassic chronology is best deciphered on the basis of ammonoid zones; pelecypods also are used to a limited extent. Pelecypod facies with a few or no ammonoids appear to be very widespread in South China and Japan. Where identifiable ammonoids are lacking, precise age determination of any Lower Triassic deposit is extremely difficult, if not impossible. This dependence on ammonoids for a chronological framework has often been a mixed blessing, since faulty identifications have frequently led to erroneous conclusions on correlation and paleogeography in the Circum-Pacific region.

The understanding of Lower Triassic chronology and the sequence of ammonoid zones now in widespread use are largely due to the researches of L. F. Spath (1930, 1934, 1935, 1951). One of the most significant aspects of Spath's contributions was his demonstration of the general incompleteness of the fossil record. The tendency had been to interpret the ammonoid faunas of a particular region as representing a complete or nearly complete record of Lower Triassic time. Welter (1922), for instance, made this interpretation from the Timor faunas, and Smith (1932) likewise from the faunas of the western United States. The only large Lower Triassic faunas in the Circum-Pacific region are the one from Timor and the one from western United States; practically all other records of ammonoids are of very small faunas, mostly not well preserved. The interpretation of these small and isolated faunas has most often been by comparison with those described by Waagen (1895) from the classic Salt Range, and those from the Himalayas described by Diener (1897). These studies were all made prior to World War I, and did not take account of the advances that had been made in the nomenclature of these faunas and in understanding of their stratigraphic distribution. This has led to continued use of obsolete zonal concepts and taxonomic names; the misinterpretation and use of *Meekoceras* zones is typical.

A tentative correlation of Lower Triassic deposits in the Circum-Pacific region is presented in Table 1. As the chart includes only those formations which contain ammonites, many regions (e.g., in Tonkin and in parts of South China) with Lower Triassic deposits from which only pelecypods are yet known have been omitted. The sequence of ammonoid zones is that used in the Treatise volume on ammonoids (Kummel *in* Arkell *et. al.*, 1957) and is modified only slightly from that proposed by Spath (1934). The grouping of these zones into ages or divisions proposed by Spath has certain advantages in the present state of knowledge. This applies especially to the lower half of the Scythian, where several small faunas are known which are insufficient for precise zonal identification, but which can be assigned fairly accurately to one or another division or age.

Once each of these faunas is appraised in terms of its proper chronological position, the remarkable homogeneity of the Lower Triassic ammonoid faunas of the Circum-Pacific region becomes apparent. Even superficial examination of the fossils of the *Anasibirites multiformis* zone from Timor, Hupeh in China, Shikoku in Japan, British Columbia, and western United States is sufficient to indicate clearly the identity of these faunas. This also tends to emphasize the lack of special faunal provinces in the Circum-Pacific region, at least in so far as ammonoids are concerned. Many previous statements on correlation and zoogeography of Lower Triassic strata of the Circum-Pacific region, and on ammonoids of this region, which differ from the interpretation presented here, have been based on comparisons of faunas which are not contemporaneous.

Timor

One of the best preserved series of Lower Triassic faunas known from the Circum-Pacific region is that described by Welter (1922) from the island of Timor. These faunas, however, do not represent as long a span of Early Triassic time as Welter originally concluded (Spath, 1934). The faunas belong to the Flemingitan and Owenitan ages except that from "Block E bei Nifoekoko", which is Prohungaritan in age. In lithology, the rocks with these faunas are a carbonate cephalopod facies.

China

The widespread occurrence of Lower Triassic formations in South China has long been known, but the lack of comprehensive paleontological reports, especially on the ammonites, has handicapped interpretation of the record. The only monographic treatment of Lower Triassic ammonoids is by Tien (1933), and small but very interesting faunas

TABLE 1.—Correlation of Lower Triassic (Scythian) Ammonoid-bearing Strata in the Circum-Pacific Region.

Divisions	Zones			China			Japan		Siberia		North America				
		New Zealand	Timor	Kweichow	Hupeh	Kiangsu	Shikoku	Kwanto Mountain Land	Ussuri Region	Kolyma Region	Alaska	Western	California	Nevada	Idaho–Utah
Prohungaritan	*Prohungarites similis*		X	?											X
Columbitan	*Columbites parisianus*								X						X
	Tirolites cassianus														X
Owenitan	*Anasibirites multiformis*		X		X	X	X					X			X
	Meekoceras gracilitatus	X	X					X		X			X	X	X
Flemingitan	*Flemingites flemingianus*		X	?					X					X	X
	Koninckites volutus		X												
Gyronitan	*Xenodiscoides fallax*														
	Prionolobus rotundatus			?					X			?		X	X
	Proptychites rosenkrantzi										X				
	Visnuites decipiens														
Otoceratan	*Ophiceras commune*			X	X	X		X			X	?			X
	Otoceras woodwardi										X				

of ammonites from South China have been described by Hsu (1936, 1937). A monographic study of the Triassic fossils of Yunnan has apparently been prepared by T. H. Yen and T. Y. Hsu, but has never been published (*fide* Hsu, 1937; Hsi-chih, 1947).

The faunas described by Tien (1933) came from a number of localities in the provinces of Kweichow and Hupeh. At Paomochung, Kweichow, a dark limestone bed lying directly upon the Permian coal series yielded *Ophiceras* (*Lytophiceras*) *sinensis* Tien, *Ophiceras* (*Lytophiceras*) *tingi* Tien, *Ophiceras* (*Lytophiceras*) cf. *demissum* (Oppel), and *Pseudosageceras paomochungensis Tien.* This fauna indicates the *Ophiceras* zone, so well known from the classic Himalayan and East Greenland localities. From other localities at Kweichow, at a horizon a little higher than the strata with the *Ophiceras*, Tien described *Koninckites falciplicatus* (Tien), *Koninckites ellipticus* (Tien), *Paranorites kueichowensis* (Tien), and *Paranorites evolutus* (Tien). The first of these species was originally described as a species of *Clypeoceras* and the others as species of *Meekoceras*. The genera *Koninckites* and *Paranorites* are common forms in the classic Salt Range section, and are Gyronitan and Flemingitan in age. At another locality, *Meekoceras* cf. *jolenkense* Krafft was identified. This specimen belongs to the genus *Prionolobus,* which has about the same age span as *Koninckites* and *Paranorites*. It is not possible from the data available to place these particular ammonoid faunas in a precise zone, but it can at least be concluded that one or more ammonoid zones are represented which are younger than the *Ophiceras* beds, and represent the Gyronitan and/or Flemingitan ages.

Finally, from another locality in Kweichow, Tien tentatively referred a single specimen to *Palaeophyllites* cf. *steinmanni* Welter. This particular species is known only from the *Prohungarites similis* zone of Timor. However, Tien's specimen is quite different, and this suggested identification must be left in doubt.

Tien had material from two localities in Hupeh, of which only one yielded specimens which the author considers to be identifiable. This collection, from Nienyuya, 2 li west of Nanchiaopu, Chingmen, contained *Anasibirites* cf. *kingianus* Waagen, *Kashmirites obliquecostatus* Tien, *Kashmirites* aff. *subarmatus* Diener, and *Kashmirites acutangulatus* Welter. These are well-known genera which characterize the *Anasibirites multiformis* zone in several localities in the Circum-Pacific region.

Hsu (1937) described *Ophiceras demissum* (Oppel), *Ophiceras* (*Lytophiceras*) *commune* Spath, and *Ophiceras* (*Lytophiceras*) cf. *sakuntala* Diener from the lower part of the Tayeh limestone in western Hupeh. These identifications seem reasonably correct, and are another record of the *Ophiceras* zone.

A number of reports on Triassic stratigraphy of South China have included lists of ammonoids unaccompanied by descriptions or illustrations. Since many of these identifications are doubtful, only brief mention of some of them will be made, and final judgment will have to await more paleontological data. In a comprehensive report on the

Lower Triassic Chinglung limestone exposed in the lower Yangtze Valley around Nanking, Chi, Hsu, and Sheng (1936) recorded two distinct ammonoid zones. Specimens from these zones have been described by Hsu (1936). The fauna in the lower part of the Chinglung limestone contains *Gervilleia subpannonica* Krumbeck, *Ophiceras* sp., *Meekoceras hodgsoni* var. *involutum* Hsu (*Prionolobus*?), *Otoceras* cf. *woodwardi* Griesbach, and *Pseudosageceras* sp.ind. Of particular interest here is the presence of *Otoceras* cf. *woodwardi*, the index species for the lowest zone of the Scythian. This species (or closely related forms) has previously been known only from the Himalayas and from East Greenland. The writer has an as yet undescribed specimen from northern Alaska. From a higher horizon at another locality close to Nanking, *Xenodiscus* sp., *Tirolites* cf. *spinosus* Mojsisovics, *Tirolites* sp.nov.ind., *Anasibirites* sp., and *Celtites* sp. were recorded. Chi, Hsu, and Cheng (1936) and Hsu (1936), who described the fauna, noted that it is representative of the *Anasibirites* zone and the *Tirolites* zone. However, from the description and illustrations, the tirolitids and celtitids appear to belong to *Xenoceltites*. If this determination is correct, it appears unlikely that the *Tirolites* zone is represented. These authors recorded the bed from which these fossils were collected as 42 metres thick and gave no indication of how these species are distributed within it.

What appears to be potentially the largest and zonally the most complete representation of Lower Triassic ammonoids in South China has been recorded by Chao (1947) from western Kwangsi. Chao reported more than 60 genera, of which he mentions *Ophiceras*, *Meekoceras*, *Koninckites*, *Prionolobus*, *Kingites*, *Paranorites*, *Pseudosageceras*, *Kashmirites*, *Anakashmirites*, *Pseudaspidites*, *Flemingites*, *Proptychites*, *Ussuria*, *Anasibirites*, *Columbites*, *Subcolumbites*, *Parahedenstroemia*. As suggested by Chao, it seems likely that all the main zonal divisions of the Lower Triassic are represented. Evaluation of this fauna will have to wait until descriptions and illustrations have been published.

Japan

Lower Triassic faunas are known from only a few localities in Japan, but in recent years data have been accumulating at an ever-increasing rate through the activities of a large number of Japanese workers. In most formations of this age, pelecypods appear to predominate, as few ammonites have been described. The best known and largest Lower Triassic ammonite fauna is that described by Yehara (1928) from the Taho formation exposed at the village of Taho on the island of Shikoku. This Lower Triassic formation consists of sandstone, shale, chert, and limestone, in an unknown structural relationship with Permian strata of somewhat similar lithology containing *Neoschwagerina craticulifera* (Yabe and Shimizu, 1933, p. 90). The ammonites described by Yehara came from one of the lower limestone beds, only 13·5 cm thick, the main portion of which yielded ammonites, but the lowest part contained typical Lower Triassic pelecypods. The majority of ammonite species from the Taho formation belong in *Anasibirites* and *Hemiprionites*; Yehara had erroneously assigned these species to *Meekoceras*, *Kymatites*, *Ophiceras*, and *Xenodiscus*. This fauna is clearly representative of the zone of *Anasibirites multiformis*, which is known from Timor, the provinces of Kiangsu and Hupeh in China, British Columbia, and from Utah and Idaho in the United States.

The important contribution by Sakagami (1955) has been mentioned already. This small fauna from the Iwai formation of the Kwanto Mountain region most probably belongs to the zone of *Meekoceras gracilitatus* rather than being partly earlier Scythian in age. In the same region, north of the Sanchu Graben, Ichikawa and Yabe (1955) have recognized and described *Eumorphotis multiformis shionosawensis*, a typical Scythian pelecypod, from an exotic block of limestone in the midst of a terrain of a Lower Permian formation. Furthermore, the presence of an early Scythian ammonite zone is indicated by the intriguing discovery of *Glyptophiceras japonicum* Nakazawa and Shimizu (1955) in a cobble from Hyogo Prefecture. This remarkable specimen, which has been well illustrated and described, is clearly closely related to similar forms from the *Ophiceras* beds of the Himalayas and East Greenland. Unfortunately, the cobble was found in a region of Permian formations where no exposures of Mesozoic formations have been recognized as yet. In the adjoining Kyoto Prefecture, typical Lower Triassic species of *Claraia* and *Eumorphotis* have recently been described from the Yakumo group by Nakazawa (1953). These pelecypods do not enable any refinement of correlation other than to identify these beds as Lower Triassic in age. Nakazawa mentioned the presence of ammonites, but did not discuss or describe them. Scythian ammonoids are also stated to be present in the lower part of the Iwai group exposed in the Kitakami Mountainland of northern Honshu, but these have not been described or illustrated (Kobayashi, 1941). Ichikawa (1950) recorded *Ophiceras* s.l.sp., prohungaritoid, pseudharpoceratoid, and xenodiscoid ammonoids, and *Eumorphotis* aff. *telleri* Bittner from the Oosawa formation of the Iwai group. The description of these forms is awaited with interest.

Eastern Siberia

Extensive outcrops of Lower Triassic strata in the South Ussuri coastal region around Vladivostok have attracted the attention of numerous students of the Triassic ever since Dienar (1895) first monographed the ammonites from this region. In addition to ammonites, these strata contain a rich and diverse fauna of pelecypods, monographed by Kiparisova (1938). The stratigraphy of these Lower Triassic formations has been summarized by Kiparisova (1945), who recognized four main units which she referred to (from bottom to top) as (a) the Basal beds, (b) *Meekoceras* beds, (c) *Flemingites* beds, and (d) *Subcolumbites* beds.

The Basal beds consist of conglomerate with a sandstone matrix and cobbles of Permian limestone and granite, which rests unconformably upon eroded Permian deposits and at places on Permian granites. The sandstone cement contains *Protophiceras nicolai* Diener, *Grypoceras* cf. *hexagonale*, *Gervillia exporrecta*, *Myophoria laevigata* *Anodontophora canalensis*, etc. The thickness of these basal beds varies from 10 to 75 metres.

The *Meekoceras* beds consist of calcareous sandstones with bands of clay shale and lenses of "shell rocks", 100 to 200 metres thick. The lower portion of the *Meekoceras* bed is said to contain mainly pelecypods, among which are recognized *Velopecten minimus* Kiparisova, *Velopecten bittneri* Kiparisova, and *Pseudomonotis multiformis* Bittner. In the middle part of this unit, ammonoids predominate, including the following genera: *Meekoceras*, *Proptychites*, *Ophiceras*, *Paranorites*, *Koninckites*, *Ussuria*, *Pseudosageceras*, *Gyronites*, *Xenoceltites*, *Kashmirites*, and *Cordillerites*. Kiparisova correlated these beds with the Lower Ceratite limestone and the Ceratite marls of the Salt Range and with the so-called "*Meekoceras*" beds of the Himalayas which encompass several zones of Gyronitan and Flemingitan age. These collections were not made systematically bed by bed, and, considering the great thickness of the unit (200 to 300 metres), it is probable that several zones of Gyronitan and Flemingitan age are represented.

These particular beds had long been known as the "*Proptychites* beds", and Kiparisova's abandonment of this name for "*Meekoceras* beds" merely adds to the confusion that has arisen from misinterpretations of the genus *Meekoceras* in the Himalayan sequence.

The *Flemingites* beds consist of thin bedded sandstones containing *Flemingites prynadai* Kiparisova (n.nudum) and *Proptychites latifimbriatus* de Koninck, plus a large fauna of small pelecypods. This horizon Kiparisova correlated with the Ceratite sandstone of the Salt Range, the *Hedenstroemia* beds of the Himalayas, and the *Meekoceras* zone of western North America—horizons which are probably not contemporaneous.

It appears that the thickness and extent of the *Flemingites* beds are still unknown; in places they are only one metre thick. On the Russian Island, the *Meekoceras* beds are overlain by thin bedded sandstones alternating with clay shales. In the lower part of this sequence, *Tropiceltites inopinatus* Kiparisova (n. nudum) occurs, and 30 or 40 metres higher a limestone band a half-meter thick contained *Subcolumbites multiformis* Kiparisova (n. nudum), *Prosphingites globosus* Kiparisova (n. nudum), *Megaphyllites immaturus* Kiparisova (n. nudum), *Parannanites suboviformis* Kiparisova (n. nudum), *Parannannites gracilis* Kiparisova (n. nudum), *Pseudosageceras simplex* Kiparisova (n. nudum), *Pseudosageceras simplex* Kiparisova (n. nudum) *Grypoceras ussuriense* Kiparisova (n. nudum), *Orthoceras subcampanile* Kiparisova (n. nudum). This is a most intriguing mixture of uppermost Scythian and Anisian genera which the author correlates with the *Subcolumbites* beds of Albania and assigns to Spath's Prohungaritan division. The new species published as *nomina nuda* by Kiparisova (1945) are illustrated and briefly described in the recently published Russion Treatise volume on Mesozoic ammonoids.

A fauna of *Meekoceras* zone age from the source region of the Kolyma River described by Popov (1939) is mentioned above.

Alaska

For many years only the Upper Triassic had been recognized in Alaska, but during the recent extensive exploration programme in northern Alaska by the U.S. Geological Survey, among many interesting discoveries, Lower and Middle Triassic faunas have been recognized. Lower Triassic ammonoids were collected from the upper part of the Sadlerochit formation of the Canning River region of north-eastern Alaska. The small fauna available to the author for study includes such forms as *Otoceras boreale* Spath, *Ophiceras* cf. *tibeticum* Griesbach, *Ophiceras (Lytophiceras) commune* Spath, *Ophiceras greenlandicum* Spath, *Proptychites* cf. *rosenkrantzi* Spath. This fauna is nearly identical to the Lower Triassic fauna described by Spath (1930, 1935) from East Greenland, and is also remarkably similar to faunas from the Himalayas. The zones of *Octoceras woodwardi* and of *Ophiceras commune* of Otoceratan age are both represented, together with the zone of *Proptychites rosenkrantzi* of Gyronitan age.

Western Canada

The Triassic system is extensively developed in western Canada, especially in the middle and upper part. The Lower Triassic (Scythian) is also fairly widespread, but as yet has yielded few ammonites. The only well-preserved fauna found to date belongs to the *Anasibirites* zone (McLearn, 1945). This fauna contains species of "*Prionites*", *Wasatchites*, *Anawasatchites*, and *Xenoceltites*. Even though the genus *Anasibirites* is absent, the other genera afford close correlation with the Idaho and Utah faunas of the *Anisibirites* zone.

Warren (1945) records *Claraia stachei* from a bed at or near the base of the Sulphur Mountain member of the Spray River formation in Alberta. A black magnesian limestone bed containing many flattened ammonites is closely associated with this *Claraia stechei* bed, although not so far found in the same sections. Although the state of preservation of these ammonites prohibits specific identification, Warren considers that they include the genera *Ophiceras, Proptychites,* and *Otoceras*. This is a very important discovery, and it is unfortunate that more positive identification cannot be made. This fauna is probably lower Scythian, but its exact age will remain in question until better material is found.

Western United States

The Triassic formations of western United States contain one of the most complete sequences of ammonoid zones in the Circum-Pacific region. However, even here many gaps still exist in the record, and several zones are poorly known. Monographic treatment of the most common faunas is to be found in Smith (1932), and detailed discussion of the stratigraphy of the Idaho area and documentation on additional faunal zones in Kummel (1954).

The Otoceratan age (*Ophiceras* zone) is represented in the lower Dinwoody formation of Idaho and Montana, where Newell and Kummel (1942) and Kummel (1954) recognized the following ammonites: *Ophiceras* cf. *greenlandicum* Spath, *O.* (*Lytophiceras*) cf. *O. commune*

Spath, *O.* (*Glyptophiceras*) *nielseni* Spath, *O.* (*Discophiceras*) *subkyokticum* Spath, *O.* (*Metophiceras*) *subdemissum* Spath. In other areas in western United States where faunas of Otoceratan age have been reported, the evidence is inconclusive. Muller and Ferguson (1939) recorded *Claraia clarai*, *C. stachi*, and *C. aurita* from the lower part of the Candelaria formation in south-western Nevada, and they tentatively placed this fauna in the *Otoceras* zone. These species of *Claraia* are good index fossils of the Scythian, but they range above the *Otoceras* zone. Three similar species of *Claraia* (*C. stachei, C. clairai occidentalis,* and *C. mulleri*) have been recorded from the "Claraia" unit of the Dinwoody formation in south-eastern Idaho and western Wyoming at a horizon younger than the *Otoceras* zone (Newell and Kummel, 1942).

The Gyronitan and Flemingitan age of the upper Dinwoody formation has recently been established by the discovery of two small faunas in south-western Montana. The lowermost fauna contains species referred to *Prionolobus* n.sp. cf. *P. atavus* (Waagen) and *Koninckites* cf. *K. truncatus* (Spath). About 70 ft above this fauna the following ammonites occur: *Kymatites* n.sp. cf. *K. radiosum* (Waagen), *Koninckites* n.sp. cf. *K. timorense* (Wanner), and *Xenodiscoides* cf. *X. involutus* (Frech). At another locality, approximately 100 feet above the lower shale member of the Dinwoody formation, one small ammonite, *Gyronites* cf. *G. frequens* Waagen, has been found.

Prionolobus atavus and *Koninckites truncatus* occur in the Lower Ceratite limestone of the Salt Range, as does *Gyronites frequens*. These forms are Gyronitan in age. *Kymatites radiosum* occurs in the lower part of the Ceratite sandstone, and *Xenodiscoides involutus* in the underlying Ceratite marls of the Salt Range of Pakistan. Both of these species are Flemingitan in age. The material is too scanty and poorly preserved to allow definite identification of zones at the present time, but it clearly indicates Gyronitan and Flemingitan ages.

In south-western Nevada, Muller and Ferguson (1939) recognized a *Proptychoites* fauna overlying their Claraia fauna in the lower Candelaria formation. Their *Proptychites* fauna contains:

Hedenstroemia (*Clypites*) cf. *H.* (*C.*) *evolvens* Waagen
Meekoceras cf. *M. lilangense* Krafft
Meekoceras cf. *M. tenuistriatum* Krafft
Proptychites cf. *P. ammonoides* Waagen
Proptychites cf. *P. trilobatus* Waagen
Grypoceras cf. *G. brahmanicum* (Griesbach)
Grypolepis? sp.

According to Spath (1934), *Meekoceras lilangense* Krafft belongs in *Prionolobus,* and *Meekoceras tenuistriatum* is a transitional form between *Kingites* and *Proptychites. Meekoceras lilangense, Meekoceras tenuistriatum,* and *Grypoceras brahmanicum* have been known previously only from the so-called "Meekoceras" beds of the Himalayas. *Proptychites ammonoides, Proptychites trilobatus,* and *Hedenstroemia* (*Clypites*) *evolvens* are known only from the Ceratite marls of the Salt

Range. Muller and Ferguson assigned their *Proptychites* fauna to the Gyronitan division of Spath. It is correlative with the horizon of *Prionolobus* n.sp. cf. *P. atavus, Koninckites* cf. *K. truncatus,* and *Gyronites* cf. *G. frequens* of the Dinwoody formation in south-western Montana.

As can be seen, the Lower Scythian is as yet very incompletely known, but in the Upper Scythian all of the zones and ages are well represented. Nowhere else in the world are Upper Scythian so well displayed in continuous stratigraphic sequence. The *Meekoceras* zone is known from many outcrops in California, Nevada, Utah, and Idaho, and contains more species than any other Lower Triassic zone in western United States. The rich *Anasibirites* fauna which occurs immediately above the *Meekoceras* zone was first described by Mathews (1929) from Fort Douglas, Utah, and has since been found in south-eastern Idaho (Kummel, 1954). The *Tirolites* zone is recognized from a few species of *Tirolites* and one of *Dalmatites* which occur approximately 800 ft above the limestones with *Meekoceras* in Paris Canyon, Idaho. The *Columbites* fauna is unique to the Idaho region. Descriptions and illustrations of the *Meekoceras, Anasibirites, Tirolites,* and *Columbites* faunas can be found in Smith (1932). A monographic revision of these faunas is in progress by the writer. Discussion of the stratigraphic and paleoecologic relations of the strata enclosing these faunas can be found in Kummel (1954, 1957).

In the uppermost part of the Thaynes formation, a new ammonoid fauna has been found which includes the following forms:

Prohungarites n.sp. cf. *P. similis* Spath
Prohungarites n.sp. cf. P. crasseplicatus (Welter)
Svalbardiceras sp.
Metahedenstroemia n.sp.
Keyserlingites n.sp. cf. *K. subrobustus* (Mojsisovics)
Isculitoides n.sp.
Epiceltites n.sp. cf. *E. genti* Arthaber
Czekanowskites? sp.
Stacheites sp.
Olenikites? sp.

Prohungarites similis and *P. crasseplicatus* are known only from the Upper Scythian beds of Timor. *Svalbardiceras, Keyserlingites subrobustus, Czekanowskites,* and *Olenikites* are known only from Upper Scythian beds of the Olenek River region of northern Siberia and in Spitzbergen. *Metahedenstroemia, Isculitoides,* and *Epiceltites* are known from Upper Scythian beds in Albania and the Island of Chios, off the coast of Turkey.

When Spath (1934) proposed the Prohungaritan age as the upper division of the Scythian, he emphasized the incompleteness of existing knowledge of the uppermost beds of the stage. He recognized the close affinities of the *Subcolumbites* fauna of Albania with the *Prohungarites* fauna of Timor. However, there was little to correlate them with the "*Hungarites*" *middlemissi* beds of Kashmir or the faunas of the Olenek region in Siberia or Spitzbergen. The Upper Scythian fauna from Chios recently described by Renz and Renz (1948) substantiates the close relationship of the *Subcolumbites* fauna of Albania and the *Prohungarites* fauna of Timor. Neither of these faunas has much in common with the Arctic or Himalayan faunas mentioned above. The *Prohungarites* fauna of Idaho is an important link in correlating these Tethyan faunas with the Boreal faunas of Siberia and Spitzbergen. The Idaho *Prohungarites* fauna occurs about 1,000 ft above the *Columbites* zone. The association of these Boreal and Tethyan elements in this zone strongly verifies Spath's arguments for the establishment of a Prohungaritan age. Spath (1934) included the Spitzbergen, Olenek, Kashmir, Albanian, and Timor faunas in his Prohungaritan age, but was uncertain as to their correct zoning. The Idaho fauna found clearly demonstrates the age relationships of these Tethyan and Boreal faunas, but more detailed paleontological work is needed to establish the proper zonal relationships.

SYSTEMATIC DESCRIPTIONS

Family PROPTYCHITIDAE Waagen, 1895

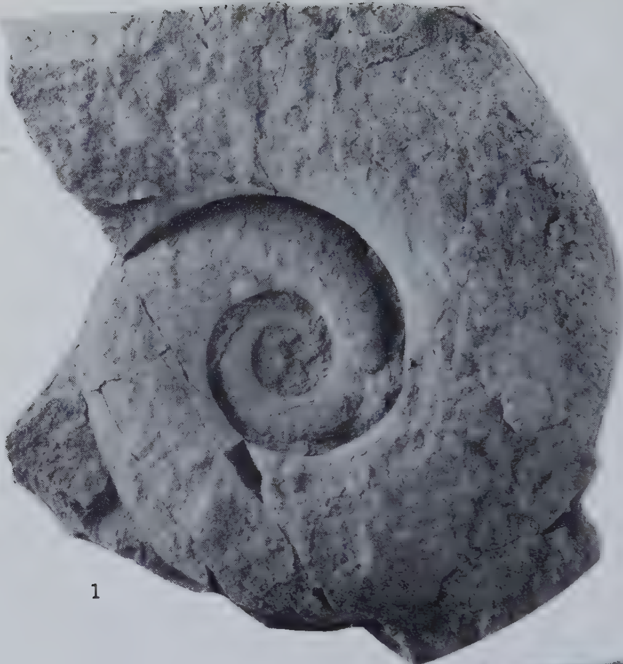
Subfamily OWENITINAE Spath, 1934

Owenites cf. *O. koeneni* Hyatt and Smith. Figs 2–4

Owenites koeneni Hyatt and Smith, 1905, p. 83, pl. 10, figs 1–22.
Owenites koeneni, Frech, 1908, pl. 63, fig. 7.
Owenites koeneni, Smith, 1932, p. 99, pl. 10, figs 1–22.
Owenites koeneni, Spath, 1934, p. 105, fig. 57a–c.

This very distinctive Middle Scythian ammonoid genus has long been known from the island of Timor, and from California, Nevada, and Idaho in the United States. The discovery of three specimens belonging to this genus from the Malakoff Hill, Coal Creek, Wairaki Downs, is of particular stratigraphic and zoogeographic interest for interpretation of the Lower Triassic history of the whole Circum-Pacific region. One of the available specimens preserves only a part of the flank of the outer whorl and a small area of the venter; the whole umbilical region is featureless through poor preservation. The other specimen, illustrated here as Figs 2–4, is more complete and shows the critical morphological features. This specimen measures 40 mm in diameter, 10 mm in the height of the last whorl, and the diameter of the umbilicus is 15·8 mm.

Owenites is characterized by its involute, compressed conch, with converging, slightly arched flanks, and narrowly rounded to acute venter. The inner whorls are more depressed and rounded. The New Zealand specimens display all of these main features but differ in details from either the American *O. koeneni* Hyatt and Smith or the Timor *O. egrediens* Welter. The New Zealand specimen figured is more compressed and less inflated in the umbilical region, and is particularly distinctive for its low and broadly rounded umbilical shoulder on the outer whorl. Here the flank merges evenly on to the flanks of the preceding whorl. *Owenites egrediens* has a more inflated conch and very well-rounded and pronounced umbilical shoulders, and the umbilical wall slopes at an angle of approximately 45 degrees. This feature, along with a tendency toward excentrumbilication, gives the whole umbilical region



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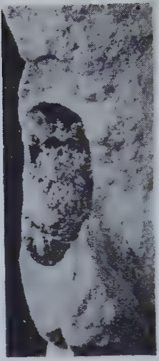

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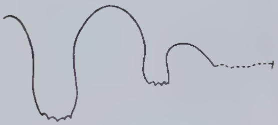

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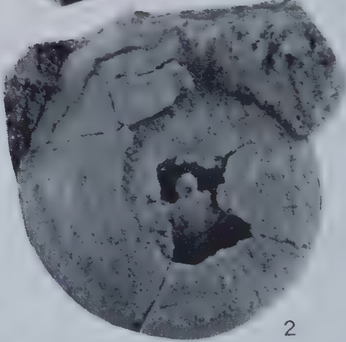

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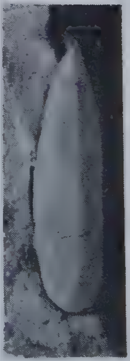

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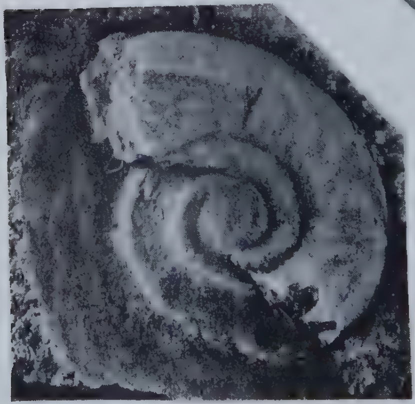

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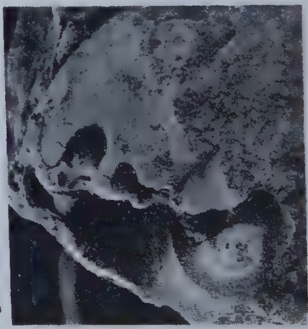

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Fig. 1.—*Flemingites* cf. *lidacensis* Welter. Malakoff Hill group, GS 5685, Coal Creek, Wairaki Downs. × 1.
Figs 2–4.—*Owenites* cf. *O. koeneni* Hyatt and Smith. Malakoff Hill group, GS 5685, Coal Creek, Wairaki Downs. × 1.
Figs 5–6.—*Wyomingites* cf. *aplanatus* (White). Malakoff Hill group, GS 5685, Coal Creek, Wairaki Downs. × 2.
Fig. 7.—*Subvishnuites welteri* Spath. Malakoff Hill group, GS 5685, Coal Creek, Wairaki Downs. × 2.

a funnel-shaped appearance. The American species, *O. koeneni*, displays the same general character of the umbilical region, though less pronounced than in *O. egrediens*. As might be expected, there is a fair range of variability in the characters of the umbilical region, degree of inflation of the conch, and nature of the venter. A large collection of specimens of *O. koeneni* available to the author from a single horizon and locality in north-eastern Nevada amply verifies this point.

The septate portion of this New Zealand specimen is very poorly preserved, and a complete suture is not visible. However, sufficient portions of the lobes, saddles, and septa are visible to indicate that there are no fundamental differences from congeric form.

LOCALITY: GS 5685, Malakoff Hill Group, Coal Creek, Wairaki Downs.

REPOSITORY: CE 1668 (figured specimen), CE 1664, N.Z. Geological Survey, Lower Hutt; CCE 12, Geology Department, Canterbury University, Christchurch.

Family FLEMINGITIDAE Hyatt, 1900

Flemingites cf. *lidacensis* Welter, fig. 1

Flemingites lidacensis Welter, 1922, p. 115, pl. 161, fig. 1.
Flemingites(?) *lidacensis*, Spath, 1934, p. 114.

A single specimen, nearly complete but showing no suture, is available. It is cast with many undulations reflecting an imperfect reproduction of the internal mould. Imperfect preservation makes the identification uncertain. In the gross features of the conch—that is, in shape and involution—the specimen is most comparable to species of *Flemingites* from Timor and the Salt Range. Typical species of *Flemingites* are characterized by strigations and radial folds of variable strength. None of these features is present on this specimen, probably because of the imperfect preservation.

The specimen measures 80 mm in diameter, and the umbilicus measures 28·5 mm. The evolute conch is compressed, the flanks gently rounded, and the venter narrowly rounded. The dimensions and general shape of the conch agree well with *Flemingites lidacensis* Welter. Because of the imperfect preservation, a more detailed analysis and comparison of the New Zealand specimen cannot be made.

LOCALITY: GS 5685, Malakoff Hill Group, Coal Creek, Wairaki Downs.

REPOSITORY: CE 1665 (figured specimen), N.Z. Geological Survey, Lower Hutt.

Subvishnuites welteri Spath, fig. 7

Vishnuites sp., Welter, 1922, p. 137, pl. 167, figs 3–5.
Subvishnuites welteri Spath, 1930, pp. 30, 90.
Subvishnuites welteri, Spath, 1934, p. 117, fig. 31.

Even though fragmentary and slightly crushed, the single specimen available can, with confidence, be recognized as conspecific with the Timor specimen originally described and illustrated by Welter (1922).

The specimen consists of a half a whorl, part of which is phragmocone showing the suture. A portion of the preceding whorl is also preserved, but the remainder of the inner whorls are gone. The conch is widely umbilicate, each whorl embracing the preceding whorl only slightly. The outer whorl is compressed and lenticular in outline; the venter is acute and the flanks broadly rounded, as are the umbilical shoulders. The suture is nearly identical with that of the Timor specimen (Welter, 1922, pl. 13, fig. 3), even in the proportions of the sutural elements.

The single specimen from Timor, representing the type of this genus and species, and this specimen from New Zealand are the only representatives known. The Timor specimen is part of the fauna from the red limestones with *Owenites egrediens.*

LOCALITY: GS 5685, Malakoff Hill Group, Coal Creek, Wairaki Downs.

REPOSITORY: CE 1667 (figured specimen), N.Z. Geological Survey, Lower Hutt.

Family MEEKOCERATIDAE Waagen, 1895

Subfamily MEEKOCERATINAE Waagen, 1895

Wyomingites cf. *aplanatus* (White), figs 5, 6.

Meekoceras aplanatum White, 1880, p. 112, pl. 31, fig. 1a–d.

Meekoceras aplanatum, Smith, 1904, p. 373, pl. 41, figs 4–6.

Meekoceras aplanatum, Hyatt and Smith, 1905, p. 146, pl. 11, figs 1–14; pl. 64, figs 17–22; pl. 77, figs 1, 2.

Flemingites aplanatus Smith, 1932, p. 51, pl. 11, figs 1–14; pl. 22, figs 1–23; pl. 39, figs 1, 2; pl. 64, figs 17–32.

Wyomingites aplanatus, Spath, 1934, p. 250, fig. 84.

A small septate fragment of a phragmocone appears to be assignable to the genus *Wyomingites.* The fragment consists of only five camerae plus a small portion of an inner whorl that is crushed. However, the distinctive cross-section of the whorl and the suture make this suggested identification possible. The whorl section is compressed, with slightly arched flanks and a broadly rounded umbilical shoulder and umbilical flanks. The venter is tabulate and aligned by sharply rounded ventral shoulders. On the fragmentary specimen available, the whorl measures 5·5 mm high and 4 mm wide. The suture, reproduced in Fig. 6, is characterized by two lateral lobes, the first of which is appreciably larger than the second, and a short auxiliary series; the ventral lobes lie entirely on the tabulate venter.

Compressed, evolute Scythian ammonoids with tabulate venters are not generally common, but at various stages in the evolution of Scythian ammonoids this adaptive type appeared. Early in the Scythian this adaptive type is represented by *Gyronites,* at a higher horizon appear certain groups of Flemingitids; in the mid-Scythian, *Wyomingites* appeared and, probably at a slightly later date, *Svalbardiceras.* In general conch form, all of these genera are quite similar, but they differ in details of whorl section, degree of involution, and in suture. They are all considered to be homeomorphous developments expressing a similar adaptation.

In whorl section and suture, the fragmentary specimen agrees well with the genus *Wyomingites*. This identification is supported by the associated forms which clearly indicate an Owenitan age. It is also similar to *Flemingites timorensis* Wanner (1911, p. 187, pl. 7, figs 1, 2) except that, in that species the umbilical shoulders are quite different, being abruptly rounded, and the umbilical wall is nearly vertical. Incomplete and immature specimens of this adaptive type are very difficult to identify with confidence, if at all. On most of these forms, the clear-cut distinguishing features appear only in the adult stages.

LOCALITY: GS 5685, Malakoff Hill Group, Coal Creek, Wairaki Downs.

REPOSITORY: CE 1666 A, B (figured specimen), N.Z. Geological Survey, Lower Hutt.

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THE ALIGNMENT OF FOLD AXES IN THE JURASSIC OF SOUTH-EASTERN OTAGO AND SOUTHERN SOUTHLAND

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Summary

In southern Southland and south-east Otago on the southern limb of the Southland Syncline each axial trace of several minor folds is sharply flexured southward to strike north-south. As normal faulting in the area has had no effect on the axial traces of folds, except in the immediate vicinity of faults, and as late-Cretaceous to Recent folding has had little or no effect on the axial traces of folds, subsequent folding and faulting does not satisfactorily explain the flexuring. A working hypothesis of a regional flexure affecting the axial trace of the Southland Syncline and of the Otago Schist Anticlinorium is proposed. In Eastern Otago the strike of bedding in subschists and greywackes of the Tuapeka Series and of the *"b"* lineation of the Otago Schists supports the hypothesis, but not unequivocally so. Field confirmation of a regional swing of strike of bedding and lineation from south-easterly inland to south-south-easterly at the coast is necessary before a regional flexure is proven. It is conjectural whether the proposed regional flexure represents a permanent swing to the south of the post-Hokonui structures or whether it denotes a local regional buckling in the south-easterly trend. The alternatives should be considered in paleogeographic reconstructions of the New Zealand region.

INTRODUCTION

Amongst New Zealand geologists there has been a revival of interest in the paleogeography of the South Pacific Ocean, east and south-east of New Zealand, particularly with regard to the possible direction of continuation of the New Zealand Geosyncline and its subsequent modification by Upper Mesozoic and Tertiary diastrophism. This interest has been largely stimulated by Wellman's bulletin on the "Structural Outline of New Zealand" (Wellman, 1956). As the axis of New Zealand Geosyncline (Wellman, 1956, p. 26, figs 2, 3, 5; Paleozoic-Jurassic) and its attendant axis of the marginal Southland Syncline meet the coastline in the south-east of the South Island, the alignment of fold axes in this area is of paramount importance in any discussion on the continuation of the New Zealand Geosyncline. The opportunity is therefore taken to describe the alignment of minor structures in the area of Permian to Jurassic sediments between the Clutha and Mataura rivers.

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The area to be discussed is covered by Provisional One Mile Series Sheets S170 (Gore), S178 (Wyndham), S179 (Balclutha), S183 (Tokanui), and S184 (Papatowai). For the general geology of the area (Fig. 1) the reader is referred to recent geological maps of New Zealand (D.S.I.R., 1958) and to Wellman (1956). Detailed geology has been described by Wood (1956) for the Gore Subdivision (S170), and by Ongley (1939) and Mackie (1935) for parts of the Balclutha Sheet (S179). Sheets S184 and S178 have been mapped by the author; the former for a New Zealand Geological Survey Bulletin, the latter as part of the four-mile mapping programme. Parts of S183 and S179 were visited during mapping of sheets S184 and S178 and other information was obtained by additional work in restricted areas of these sheets. At present the south-western corner of S183 from Waikawa Harbour westward is least known.

Occurrence of Fold Axes in the Area

The major structure is the Southland Syncline and within the area between the Clutha and Mataurua rivers it is doubly plunging. From a point two to three miles south-east of Dunvegan Station Homestead (S178, grid ref. 319206 (1943)) the syncline plunges north-west towards the Mataura River and south-east to the coast. The plunge is steeper in the south-eastern part and is variable on both sides of the point of change of plunge. The axial plane of the Southland Syncline dips steeply to the north-east. The axial trace is slightly sinuous and subdivides the area into two parts.

The north-east limb of the syncline dips steeply and minor folds (Fig. 1) have been recorded at two places. Wood (1956) mapped several in the Upper Paleozoic-Mesozoic sequence of the Gore Subdivision, and mentioned (1953) the presence of folds in the Triassic sequence north of Nugget Point. In addition, there is a small anticline four miles south-west of Clinton, along the strike from the folds in the Gore Subdivision. The axial plane of these folds is approximately vertical or dips slightly to the north-east. Near Mataura the gently dipping south-west limb of the Southland Syncline does not show minor folding. Towards the coast, however, the limb of the syncline is folded into a series of anticlines and synclines (Fig. 1), the axial planes of which may be vertical or dip steeply either to the north-east or south-west. Usually the inclination varies along the length of the fold. Most of these minor folds plunge either to the north-west or south-east, and at least one anticline Tarara Anticline) is doubly plunging. For a bulletin on Sheet S184 (Papatowai) the folds have been named as indicated on Fig. 1 and are now described in south-westwards succession from the axial trace of the Southland Syncline.

Owaka Valley Anticline

From its nose near Morris Saddle Road, Owaka Valley, this anticline extends for at least eight miles south-eastwards to the coast at

Hayward Point. Like the next fold (Jacks Bay Syncline) to the south-west, the anticline is disrupted by north-east striking normal faults, the largest of which (Settlement Fault) is shown in Fig. 1. It appears to be a doubly plunging anticline.

Jacks Bay Syncline

From Jacks Bay the syncline passes north-west to near Morris Saddle Road. It is some seven miles long, plunges to the south-east, and is disrupted by faulting.

Tarara Anticline

One of the larger folds, this anticline extends from the settlement of Tarara (S184, grid ref. 380925 (1944)) to near Melrose Station Homestead, upper Mokoreta River Valley (S178, grid ref. 080180 (1943), where the north-western nose is exposed. A doubly plunging anticline, the axial plane dips steeply to the south-west. The axial trace is about 20 miles long.

Beresford Syncline

About 20 miles long, this syncline is complementary to the Tarara Anticline. It extends north-westward from Tarara to near Garthowan Station Homestead (S178, grid ref. 063138 (1943)), upper Mokoreta River Valley. The axial plane is vertical or dips steeply to the south-west, and the axial trace is sinuous. The fold plunges gently to the north-west, forming a broad syncline, the centre of which is occupied by the almost flat-topped Beresford Range, a synclinal "mountain" range.

Tautuku Anticline

From the coastline just north of Tautuku Peninsula the anticline can be followed inland for about four miles. An anticline mapped in the upper Waikawa River Valley, some eight miles to the north-west, is assumed to be the continuation of the anticline mapped near the coast, but the linkage is tentative. There is very little positive information about the characteristics of the anticline. However, at Tautuku Peninsula and upper Waikawa Valley the axial plane dips very steeply to the north-east and sparse information together with comparison with the two anticlines mentioned above suggests that the Tautuku Anticline is a doubly plunging fold.

Fortification Syncline

Fortification Hill, a prominent feature north of Tokanui and sited at the north-west end of the syncline, provides the name for this fold. The syncline extends south-eastward for at least 22 miles, finally meeting the coastline at the east end of Waipati Beach. It plunges south-east, and its axial plane varies in inclination along the length of the fold. The strike of beds at the south (10° T) and east (140° T) heads of Tautuku Peninsula, Flaxy Head (180° T) and Chaslands Mistake (155° T) suggests that both Tautuku Anticline and Fortification Syncline close off just beyond the coast (Fig. 1).

Progress Valley Anticline

Named after Progress Valley along which it passes, the anticline extends from Quarry Hills to the coast at Teahimate Bay, a distance of approximately 12 miles. The axial plane dips steeply to the south-west, and the anticline is probably a doubly plunging fold.

Waikawa Syncline

The known axial trace of this syncline is some seven miles long and is present on both sides of Waikawa Harbour, from which the name is derived. Inland the axial trace has an east-south-east strike but swings to the south near the coast, finally emerging near Teahimate Bay, less than half a mile to the west of the axial trace of Progress Valley Anticline. It seems probable that the nose of both Progress Valley Anticline and Waikawa Syncline almost coincides with the coastline.

On the coast at Wallace Head, between the axial trace of Fortification Syncline and Progress Valley Anticline, the strata are folded into a series of small folds that are badly shattered by numerous small normal and reverse faults of throw less than 10 ft. These folds have a wavelength less than 200 yards, an amplitude of about 200 ft, and in each case the axial plane dips steeply to the north. As Wallace Head projects into the ocean very little can be deduced about the length of the axial trace of the folds, except that it is small and less than two miles. Half a mile to the east of Wallace Head, the alignment of Chaslands Mistake headland is controlled by the south-west limb of Fortification Syncline. The angle between the easterly strike of the small Wallace Head folds and the south-south-east strike of the Fortification Syncline at this point is about 40° to 50°.

West of Wallace Head the strike of the beds is about 110° T, but near Teahimate Bay where the nose of Waikawa Syncline and Progress Valley Anticline meet the coast, the strike becomes 150° T, a direction which continues to The Brothers Point two miles farther to the west. Beyond this point to Waikawa Harbour the strike is about 130° T.

During his investigation of the Waikawa Harbour sequence, Park (1887) mapped two synclines separated by an anticline. Unfortunately, the sequence west and south of Waikawa Harbour is poorly known. A study of aerial photographs covering the Tokanui Sheet (S183) indicated that the strike of beds forming the points on the coastline between Waipapa Point and Waikawa Harbour varies between 110° to 160° T, but is mostly greater than 130° T (Fig. 1).

At Waimahaka, farther to the north-west, Wood (1953) has described a south-east plunging anticline, and has discussed the close proximity of Permian and Jurassic rocks in this area.

As shown in Fig. 1, the minor folds north and south of the axial trace of the Southland Syncline are approximately parallel inland, but near the coast of South-East Otago the strike of the axial trace of several folds south-west of the axial trace of the Southland Syncline rapidly swings from 110° to 130° T to 150° to 180° T (average 170° T). Even if closure of Tautauku Anticline and Fortification Syncline does occur, the strike probably continues in the general direction of the axial trace of the folds at their southern extremity, in this case approximately north-south. There is no evidence, however, to indicate for what distance such a strike would continue. The vertical axial plane through the flexure so formed strikes east-north-east and only just impinges on the coast between Waikawa Harbour and Tautuku Peninsula. The position of the bend in the fold axes suggests that the trace of the vertical axial plane is not simple but is perhaps composed of two en echelon segments; one part for the two south-westerly folds, the other for the two north-easterly folds. The continuity is apparently modified by the small east-west striking folds in the knee of the flexure at Wallace Head. These small folds possibly formed in response to secondary compression.

On the north limb of the Southland Syncline in the vicinity of Lumsden, Coombs (1950, p. 429) suggested that an anticlinal axis was present near the base of the Upper Paleozoic(?) Roe Burn Beds. In recent mapping, Mr A. R. Mutch (pers. comm.) shows that the fold does not exist, and has mapped other folds in the sequence east of Lumsden which he considers are probably continuations of folds present in the Gore Subdivision. Mutch (1957, p. 508) mentions the occurrence of south-eastward plunging, minor asymmetric open folds in the Takitimu Group Ranges on the southern limb of the Southland Syncline. Thus, in the region of Paleozoic to Mesozoic rocks to the south of the belt of Otago Schist there is a general parallelism of the axial trace of minor folds to the axial trace of the Southland Syncline. The area in which this parallelism occurs extends from Mossburn south-eastwards to the coast where the flexuring commences.

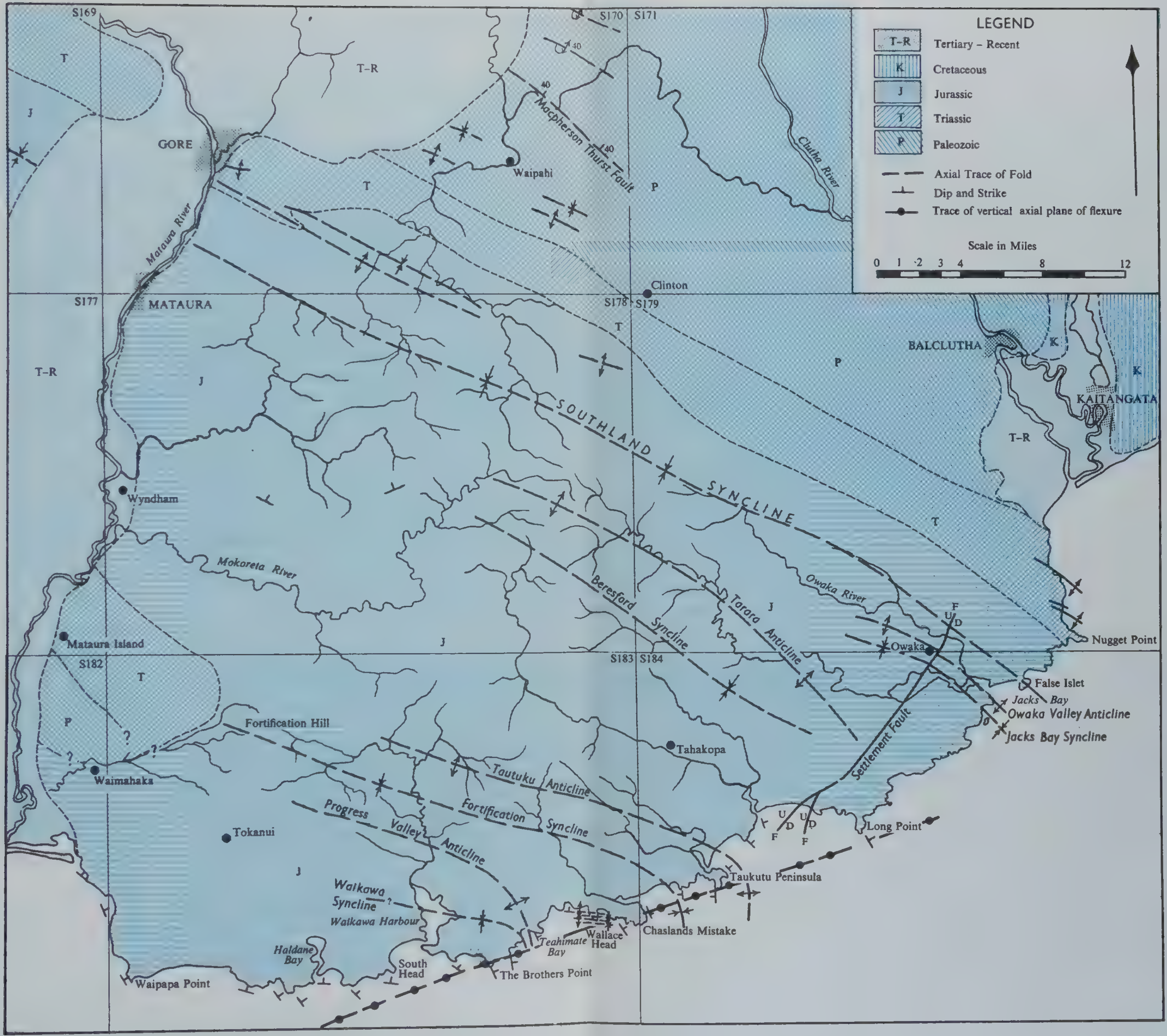

FIG. 1.—Map of South-East Otago, Eastern and Southern Southland showing distribution of folds. Geology after Mackie (1935), Ongley (1939), and Wood (1953, 1956), modified and with additions.

THE ORIGIN AND EXTENT OF THE FLEXURING

In the south-east of the South Island the structural trend of the Paleozoic-Mesozoic sediments deposited in the New Zealand Geosyncline is considered by Wellman (1956) to be due to the eversion of the geosyncline during late Jurassic-early Cretaceous times. Because of the position of the flexure near the present coastline any hypothesis on the trend of the sequence beyond the coast must be subjective.

The flexure may be explained in four ways, two of which are illustrated by Figs 2 and 3. In these diagrams the trace of the vertical axial plane of the flexure is assumed to continue in an east-north-easterly direction.

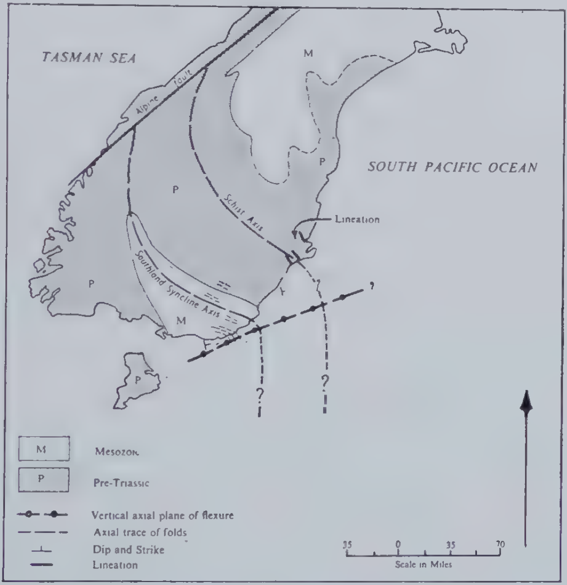

FIG. 2.—Alternative 1. A regional flexure permanently bending to the south of the Southland Syncline Axis and Schist Axis. Geology after Wellman (1956), modified.

(1) A regional flexure affecting the axial trace of both the Southland Syncline and Otago Schist Anticlinorium, with the folds bent permanently to continue in a southerly direction (Fig. 2).

(2) A regional flexure as postulated for (1) above, but only over a narrow zone so that the fold axes continue in essentially a south-easterly direction (Fig. 3).

(3) A local flexure affecting only the axial traces of folds south-west of the axial trace of the Southland Syncline.

(4) Subsequent modification of south-east (110° to 130° T) striking structures of late Jurassic-early Cretaceous age by younger faulting and folding. Beyond the affected zone the strike of the structures would be essentially the same (110° to 130° T).

The effect on late Jurassic-early Cretaceous folds of structural trends of late Cretaceous and Tertiary age as revealed in sequences adjacent to the area of Mesozoic and Paleozoic rocks between the Clutha and Mataura rivers is important for its bearing on the fourth alternative. During the Tertiary and Pleistocene in the Gore Subdivision, Wood (1956) has presented evidence for recurrent movement along an intersecting pattern of north-westerly striking fold-axes. His map and figures (Figs 2 and 3) show that this grid-iron pattern has had little if any effect on the trend of the axial trace of folds in the adjacent Paleozoic-Mesozoic sequence. Similarly, the sequence of late Cretaceous and Tertiary movements in Eastern Otago, particularly in South Otago (Ongley, 1939), has had little or no effect in the trend of late Jurassic-early Cretaceous folds in the Mesozoic sequence at Nugget Point.

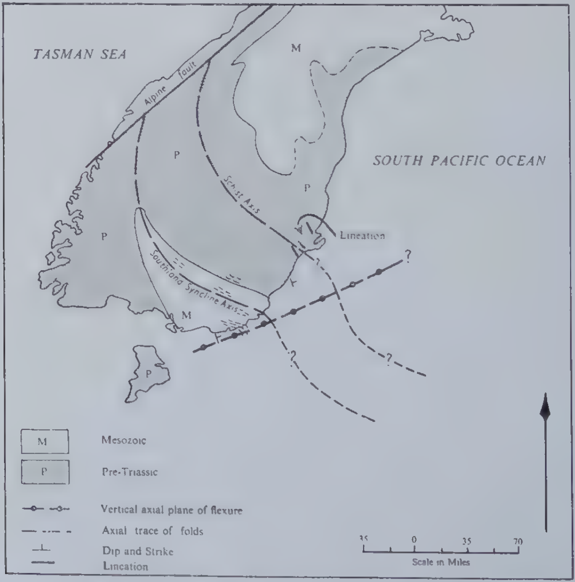

FIG. 3.—Alternative 2. A regional flexure affecting the Southland Syncline Axis and Schist Axis over a zone so that beyond the zone the fold axes continue in a south-easterly direction. Geology after Wellman (1956), modified.

Settlement Fault, the north-east striking normal fault shown on Fig. 1, is the largest of several such faults situated between Owaka and the coast. This fault, which has the greatest throw near the centre of its length and the throw decreasing towards either end, has not modified the trend of the axial trace of the Southland Syncline, Owaka Valley Anticline, or Jacks Bay Syncline, except in the immediate vicinity of the fault trace. As the fault has no large-scale effect on the three axial traces mentioned above, and as it apparently stops short of the area of most prominent flexuring, it does not satisfactorily explain the flexuring of the folds beyond its south-western extremity. The flexuring is of a larger order of magnitude than that present in the vicinity of faulting. Thus, in the area between the Clutha and Mataura rivers, except in the immediate proximity of faults, subsequent folding and faulting has had little effect on the trend of the older post-Hokonui structures and certainly nothing to compare with the flexure present along the coast. Re-folding by a major north-easterly striking upper Cretaceous or younger fold or fold-zone could explain the flexuring. Benson (1941) has shown that in Eastern Otago, between Dunedin and Kaitangata, there is a north-east striking, moderately mobile area. There is no evidence that the zone continues southwards beyond Kaitangata; nor does it appear to have modified the structural trend of the "older" rocks in Eastern Otago, and it has certainly had no effect at Nugget Point. Indeed, Ongley (1939, p. 16) has stressed the contrast between the north-west strike of the basement rocks and the north-east trend of the younger rocks. Although negative evidence, the apparent moderate intensity of Upper Cretaceous and younger folding in the south-east of the South Island is suggestive that a major zone of younger folding of sufficient intensity to strongly deform the structural trend of the basement rocks was not present near the coast.

Even though the dip (5° to 30°) of the southern limb of the Southland Syncline is gentle, because of the length of coastline (30 miles) along which folds are flexured and the prominence of the flexure alternative (3) is not easily envisaged, as the factors (folding and faulting) most likely to cause a local flexure have been discussed above and shown to have had little effect in this area.

North-east of the axial trace of the Tautuku Anticline, the most northerly flexured fold, there is no structural evidence to show that the axial trace of the Southland Syncline is bent southwards. The general trend (Fig. 1) of the Jacks Bay Syncline, Owaka Valley Anticline, and Southland Syncline suggests, however, that it is, but for further evidence on the nature of the flexure, the structure in the area of greywacke, sub-schistose and schist rocks north-east of fossiliferous Permian and Mesozoic has to be studied. In the Blue Mountains, Gore Subdivision (Wood, 1956, p. 28), the average strike of the greywacke and sub-schistose rocks south of the schists of Otago is 120° to 130° T. Marshall (1918, pp. 34-35) mentioned the difficulty in interpreting the structure in the Tuapeka Subdivision, and also recorded the variability of dip and strike of the "foliation" planes of which he concluded "the dip almost throughout has a southerly tendency, which may indicate that the great north-west—south-east anticlinorium of the south of New Zealand has a pitch towards the south-east". From the information present on Marshall's map it is difficult to amplify his comments except to agree with Ongley (1939, p. 31) that the structure present appears to be a south-east plunging syncline, the axial trace of which strikes more south-south-easterly than south-east. Farther to the east along the coast of Eastern Otago the strike of beds in the sub-schistose and greywacke rocks between Taieri Mouth and Akatore River is about 140° T, and south of the Akatore to Tokomairiro River (a distance of seven miles) averages approximately 160° T (maps of Clarendon and Akatore Survey Districts, Ongley, 1939). Although some 40 miles south-east of Blue Mountains and separated from the coastal sequence by a geologically poorly known area with perhaps variable dip and strike (i.e. Tuapeka), the structural evidence in the Tuapeka Subdivision and along the coast south of Taieri Mouth is compatible with a swing of strike to the south.

Through the work of Turner (1940) the structure of the schists in Eastern Otago is relatively well known. He (p. 77) considered "A strong lineation, tentatively selected as the *b* fabric axis, is always present in the plane of schistosity and trends between NW and 5° to 10° W of N" (Fig. A), and that "it appears to be the B-axis connected with the earliest and main phase of metamorphism", and to be unaffected by north-east trending block-faulting except in the immediate vicinity of fault planes. The average strike of the *b* lineation in Eastern Otago (Turner, 1940, Fig. A) is approximately 150° T, although near Brighton it is about 130° T. Directly north-north-westwards there is a similar area of more easterly striking lineations near Lee Stream, and the position of the two localities in relation to the more north-north-westerly striking lineations of Eastern Otago suggests that they may be areas of anomalously striking lineations at the centre of a fold, or even on the crest of the Otago Schist Anticlinorium. Information on the trend of lineations in Central Otago is sparse. As indicated by the inclination of schistosity planes, the trend of axial traces of folds evident on the maps of Williamson (1939) and Park (1906, 1908) is very sinuous. Turner (1940, p. 77) has shown that the *b* fabric axis is always present in the plane of schistosity and has much the same trend (NW to NNW or even N), so the strike of the *b* lineation is probably also variable. Turner's results are largely confirmed by Robinson (1958) who records two lineations in the Akatore-Brighton district. An earlier "fine lineation", the strike of which "ranges from about N 10° E to N 40° W", and a later "coarse lineation" which is found only in the north-eastern portion of the area and "always strikes 3° to 20° more westerly than the fine lineation, or from N 7° W to N 50° W." In the south of the area the strike of the fine lineation averages about N.-S. and farther north it averages about N 20° W. Robinson also describes a syncline near Taieri Mouth, the axial trace of which strikes south-east. The known length of the axial trace is two to three miles and is perhaps insufficient to give a regional direction. The relationship of the schist and greywacke (Wellman, 1956, fig. 2; D.S.I.R. Geological Map of New Zealand, 1958) on either side of the Titri Fault (Ongley, 1939; Mutch and Wilson, 1952) suggests that the syncline at Taieri Mouth is a continuation of the syncline present in the Tuapeka District, the axial trace of which has a south-south-easterly strike. If this suggested continuation is correct, then the axial trace of the Otago Anticlinorium on the east side of the Titri Fault would be displaced northwards relative to the trace on the west side of the fault.

Assuming the flexure to be regional and to affect the axial trace of both the Southland Syncline and Otago Schist Anticlinorium, either the first or second alternative could be feasible. In either case, because of the parallelism of fold axes, the axial trace of the Southland Syncline would bend to the south some 10 miles from the coast along the east-north-eastward extension of the trace of the vertical axial plane of the flexure. Extrapolation of the vertical axial plane farther east-north-eastwards, and because of the essential parallelism of the axial trace of the Southland Syncline to that of the Otago Schist Anticlinorium (Wellman, 1956, figs 2, 3, 5), the axial trace of the Otago Schist would also flexure to the south some 40 to 50 miles from the coast (Figs 2, 3). The location of Biotite Zone schists near Brighton by Robinson (1958) and the strikes of lineations recorded by himself and Turner (1940, fig. A) indicate that the schist axis emerges at the coast slightly farther south than shown by Wellman, and that it has a south-east to south-south-east, rather than east-south-east trend. Three possible explanations may be suggested to explain the presence of more southerly striking lineation and bedding in Eastern Otago rather than at 40 to 50 miles out to sea.

(a) If the vertical axial plane of the flexure present along the coast of South Otago continues in an east-north-easterly direction, the southerly strike in Eastern Otago could be a local feature, part of a minor sinuosity.

(b) North-westward movement of an Eastern Otago block relative to a South Otago block along a sinistral north-westerly striking transcurrent fault (Fig. 4). A fault in a suitable position to explain the differences would be the MacPherson Thrust Fault, but Wood (1956, pp. 97-98) considers this fault to be a minor feature.

(c) The third possibility is that the vertical axial plane of the flexure present along the coast of South-East Otago swings northward along the coast rather than continuing in a straight line to the east-north-east (Fig. 5).

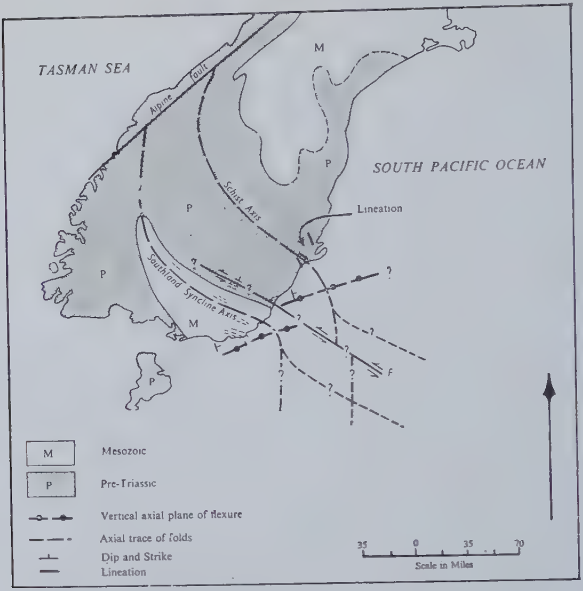

FIG. 4.—A north-west striking sinistral transcurrent fault to account for the occurrence of southerly striking bedding and lineation near the coast of Eastern Otago. Geology after Wellman (1956), modified.

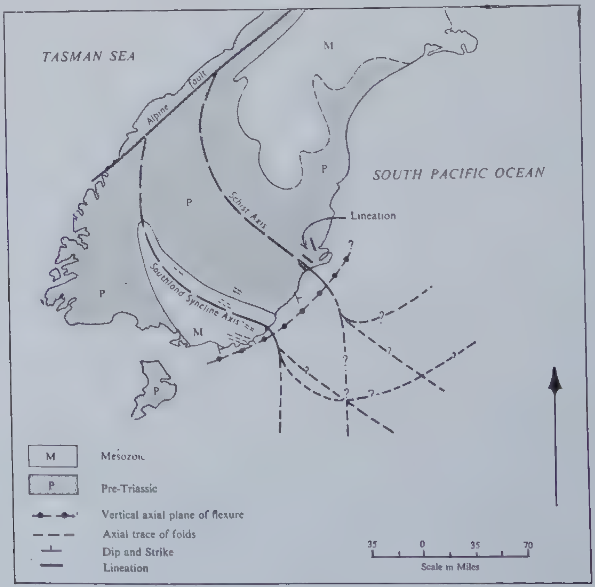

FIG. 5.—Vertical axial plane of flexure follows along the coast instead of continuing to east-north-east and thus accounts for the occurrence of southerly striking bedding and lineation in Eastern Otago. Three alternative directions are indicated for the continuation of the major fold axes beyond the vertical axial plane of flexure. Geology after Wellman (1956), modified.

Conclusions

The structural evidence available in the Mesozoic sequence along the coast of South-East Otago and Southern Southland indicates the presence of a flexure affecting the axial trace of several folds south of the axial trace of the Southland Syncline. Although north-east striking faults of large throw are present in the area they have not modified the regional strike of axial traces of folds. The length of coastline along which the flexure is present, the parallelism of the axial trace of the folds to that of the Southland Syncline, and the general trend of folds nearest to the axial trace of the Southland Syncline, suggest that the axial trace of the Southland Syncline is flexured. The more southerly strike of bedding in the greywackes and sub-schists along the coast of Eastern Otago compared with that in similar rocks inland in the Gore Subdivision is suggestive of a swing to the south. The trend of the main *b* lineation in Eastern Otago is compatible with a flexuring to the south, but insufficient is known about details of the regional trend of the *b* lineation from North-West Otago to the coast to accept unequivocally a regional flexure.

The position and trend of the axial trace of the Otago Schist and of the Southland Syncline as indicated by Wellman (1956, figs 2, 3, 5) are compatible with a hypothesis of a regional flexure to the south, in which case the sharp flexure present in the axial trace of minor folds south of the axial trace of the Southland Syncline could be a response to compression in the "knee" of a more gradual (greater radius of curvature) regional change in the trend of the axial trace of the Otago Schist and of the Southland Syncline. The presence of normal faulting near Owaka is in accordance with a regional flexure as the area outside the "knee" of such a flexure would be under tension and the strike of faults approximately parallel to the Principal Horizontal Stress.

Because the flexure present along the coast of South-East Otago is apparently inexplicable by subsequent folding and faulting, the author proposes as a working hypothesis that a regional flexure affecting the axial trace of both the Southland Syncline and Otago Schist is present beyond the coast of Otago and Southland. It is conjectural whether the proposed regional flexure has a permanent swing to the south (Fig. 3) or only represents a buckle in a regional south-east trend. The magnitude of the proposed regional flexure and the implied change in direction of application of Principal Horizontal Stress tends to support the hypothesis of permanent bending to the south of the major fold axes rather than a kink in the south-easterly trend. A southerly continuation of Paleozoic and Lower Mesozoic structures contrasts with the linkage of the schists of Otago to the Chatham Island schist via the Chatham Rise as is indicated by Wellman's (1956, fig. 3) tentative continuation of the Schist Axis to the north-east. A corollary of the concept of a permanent regional flexure to the south is that the "New Zealand Recurved Arc" as propounded by MacPherson (1946) would have another curve to the south in which case the late Tertiary-Quaternary volcanism of Eastern Otago would be in an area of tension near the convexity of the flexure and the recently described (Harrington and Wood, 1958) andesitic volcanism of Solander Island would be in the concavity.

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SEDIMENTATION OF THE ALTERNATING GREYWACKE AND ARGILLITE STRATA IN THE PORIRUA DISTRICT

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Summary

The Lower Mesozoic alternating greywackes and argillites in the Porirua district exhibit graded bedding, lamination, convolute lamination, cross lamination, mud flakes, and current markings.

The sediments, rapidly derived from a plutonic terrain, were rapidly transported and deposited by turbidity currents in the New Zealand Geosyncline. The orientation of cross lamination and current markings suggests that the turbidity currents flowed north-north-east, sub-parallel to the present regional tectonic trend.

At Porirua, sedimentation was in deep water, a considerable distance from the supplying land mass, and not far from the axis of the geosyncline.

INTRODUCTION

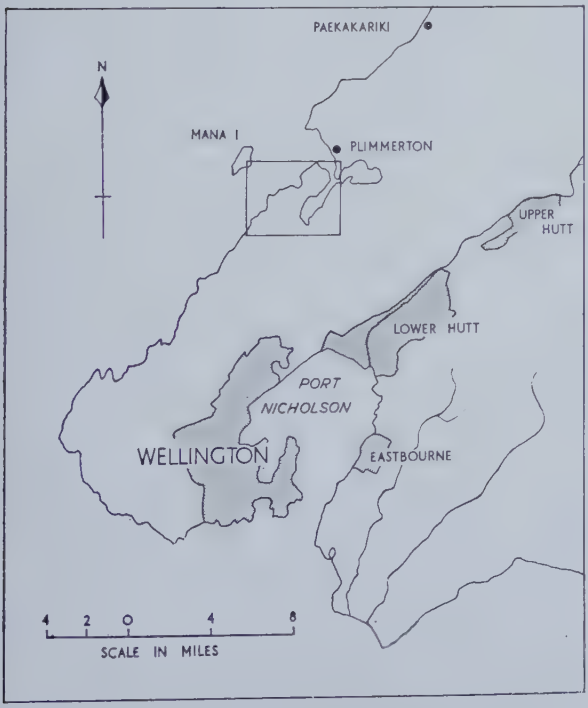

FIG. 1.—Map showing location of the Porirua district.

The Lower Mesozoic rocks of the Wellington Peninsula are predominantly unfossiliferous well indurated greywackes and argillites, with local occurrences of intraformational conglomerates, autoclastic breccias, and submarine spilitic lavas associated with red and green tuffaceous argillites, radiolarian jaspers, and grey cherts (Reed, 1957). In the Porirua district (Fig. 1), the rocks are mainly well indurated

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alternating greywackes and argillites, evenly bedded, intensely fractured, and with few fossils (Fig. 2). The rocks, apart from those exposed along the actively retrograding west coast, are affected by weathering.

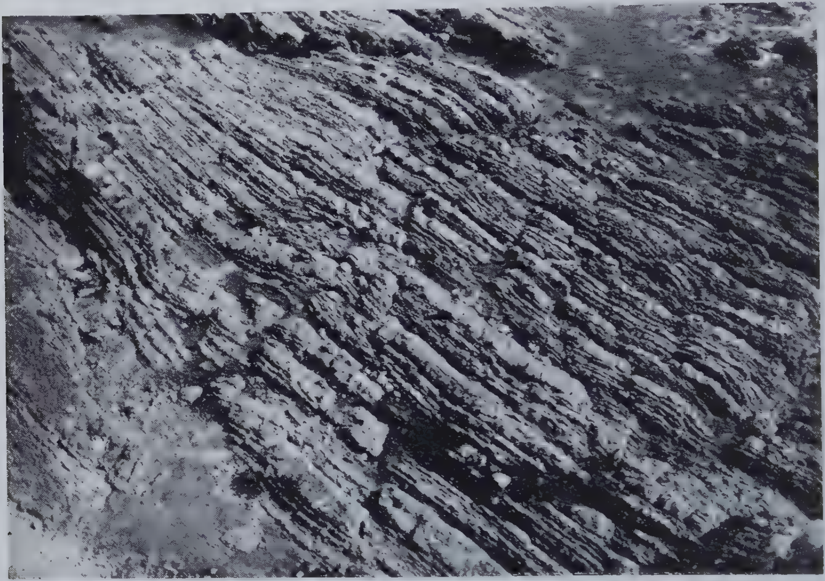

FIG. 2.—An outcrop of thinly bedded alternating strata near Titahi Bay. Note the regular bedding and the small-scale faulting. The strata shown are 100 ft thick.

The unweathered rocks on the coastal strip north-east and south-west of Titahi Bay were examined in detail (Fig. 3).

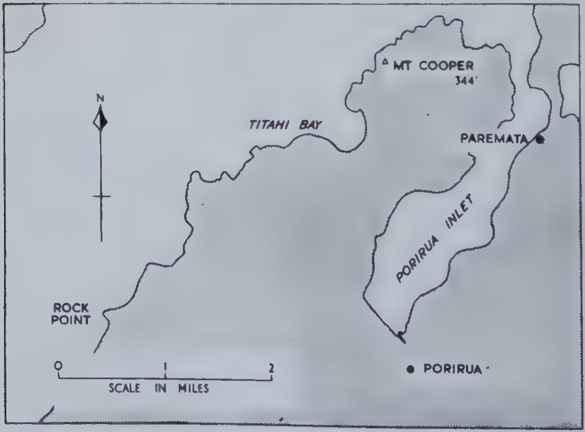

FIG. 3.—Locality map of the Porirua district.

PREVIOUS GEOLOGICAL WORK

Crawford (1869) recognized impressions of "plants and carbonized substances" in almost vertical strata on the shores of Porirua Harbour. According to McKay (1888), these "plant bearing beds extend through the hills to the shores of Port Nicholson between Ngauranga and Petone".

THE SEDIMENTS

Definition of Terms

The basic terms used in this description are defined as follows:

Stratification is the kind of rock-layering formed during deposition by changes of some kind in the materials being deposited or in the conditions of deposition, and a *stratum* is a layer so formed (Dunbar and Rogers, 1957, p. 97).

Bed and *bedding* are applied to any stratum or stratification of thickness greater than 1 cm (McKee and Weir, 1953, p. 384).

A *graded bed* is distinguished by a gradation in grain size, from coarse to fine, upward from the base to the top of a bed.

Lamina and *lamination* are applied to any stratum or stratification 1 cm or less in thickness (McKee and Weir, *loc. cit.)*.

Convolute lamination is the corrugation of depositional lamination within individual beds of a regular stratified sequence (ten Haaf, 1956, p. 188). It has also been termed convolute bedding, contortions, crinkled bedding, intraformational corrugations, penecontemporaneous or subaqueous deformation, syn-sedimentary folds, and slumping.

Cross lamination is the small-scale current ripple lamination within individual beds of a regular stratified sequence. It has also been termed micro-current bedding.

Mud flakes are fine grained mudstone (or argillite) fragments embedded in a coarse grained (greywacke) matrix within individual beds of a regular stratified sequence.

Current markings is a general term that includes both drag marks and flute casts.

Drag marks are "long, even ridges" on the base of individual beds of a regular stratified sequence (Kuenen, 1957a, p. 243).

Flute casts are "sharp subconical welts" on the base of individual beds of a regular stratified sequence (Crowell, 1955, p. 1359).

Bed facing is the direction of younging as inferred from top and bottom criteria (Moore, 1957, p. 122).

Bedding

MEGASCOPIC CHARACTERS

An individual bed consists of a coarser, lower unit of greywacke, which either grades into, or is in direct contact with, a finer, upper unit of argillite. It is separated from an overlying bed by an abrupt contact (Fig. 4).

The thickness of individual beds varies from 1 in. to more than 30 ft. A total of 290 beds were measured (N 160/392449, 109 beds; N 160/386437, 106 beds; N 160/388446, 75 beds), grouped into bed thickness classes and plotted in a histogram (Fig. 5A). The histogram is symmetrical about a maximum in the 0·5 to 1·0 ft range. Cumulative bed thickness frequencies plot on logarithmic probability paper as a straight line (Fig. 5B), and thus have a logarithmic normal distribution (Pettijohn, 1957, p. 160). The symmetry of the histogram is also an expression of this logarithmic normal distribution. The significance of the log normal bed thickness variation is uncertain. Pettijohn (*loc. cit.*, p. 161) noted that some graded bedded and current bedded sequences show log normal bed thickness variations.

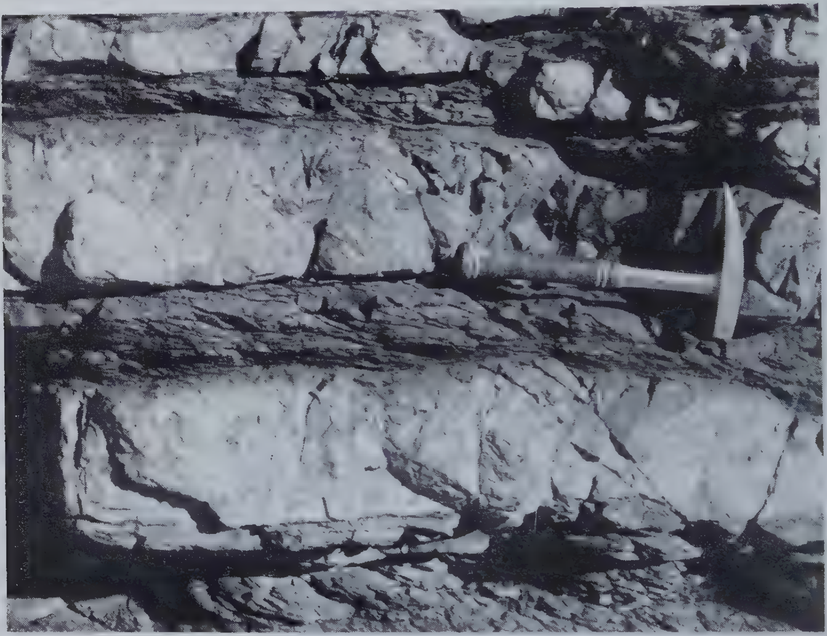

FIG. 4.—Detail of two graded beds in abrupt contact along the line of the hammer handle. Note the intense fracturing particularly in the upper argillite units.

The chief variations in grading of beds, observed in the field, are summarized in Fig. 6. Many transitions between the varieties figured have, however, been found. The various types of beds in the figure are placed in order of decreasing field occurrence.

MICROSCOPIC CHARACTERS

Two different methods were used to study microscopically representative graded beds. In one, thin sections were cut to include the whole of two consecutive thin graded beds (A and B), and the maximum grain size, under a high power objective, was measured at 1 mm intervals. Bed A is separated from bed B by an abrupt contact. Both beds show a definite, though fluctuating, upward decrease in maximum grain size (Fig. 7). The fluctuations of maximum grain size are larger in the upper limits of each bed. The larger fluctuations in bed A (the upper 4 cm of bed A) coincide with lamination and convolute lamination, and in bed B (the upper 2 cm of bed B) with lamination.

The above results and further microscopic study of random samples indicate that a typical bed has a maximum grain size approximately 0·5 mm at the base and less than 0·01 mm at the top. Usually the maximum grain size near the base is coarser in the thicker bed, than in the thinner bed.

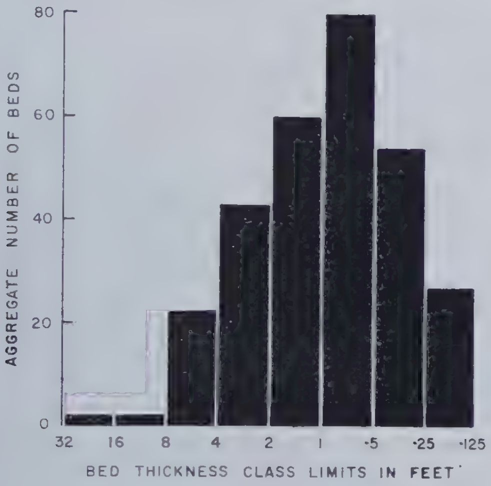

FIG. 5A.—Histogram of bed thickness frequencies.

In the other method three thick graded beds, C (92·4 cm), D (45·7 cm), and E (134·3 cm) were each sampled at five equally spaced intervals. Thin sections of the samples were analysed microscopically with a graticule eyepiece for the volume percentage coarser, and finer, than 16μ grain size. The value of 16μ was taken as an arbitrary division between coarse and fine. The progressive decrease in the volume percentage coarser than 16μ shows grading from the bottom to the top of the individual beds, apart from a small anomaly near the base of bed E (Fig. 8). A striking feature of the results is the very high volume percentage finer than 16μ, even near the base of each bed.

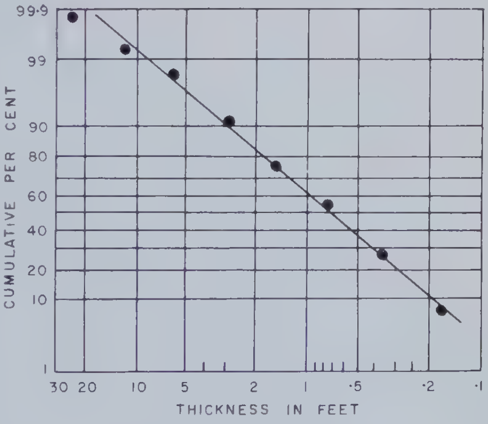

FIG. 5B.—Bedding thicknesses plotted on logarithmic probability paper.

Lamination

Lamination (Fig. 6 B and C), a common sedimentary feature in the Porirua argillites, is parallel to bedding except where affected by convolutions or current rippling. The thickness of each lamina varies from 0·5 mm to 10 mm. Some laminae exhibit micro-grading (Fig. 11).

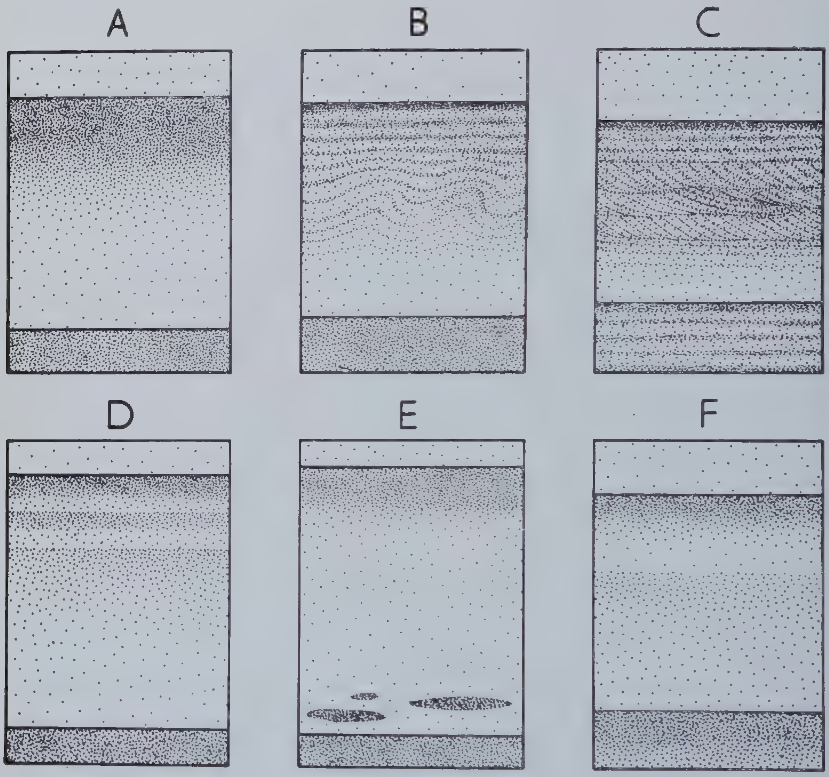

FIG. 6.—Types of graded bedding. A: graded bed without sedimentary structures. B: graded bed with convolute lamination and lamination. C: graded bed with cross lamination and lamination. D: composite graded bed with a thick primary, and thinner secondary and tertiary beds. E: bed with mud flakes near the base, and an abrupt contact between greywacke and argillite units. F: composite graded bed with a relatively fine grained primary bed which is truncated by a coarse, well graded, secondary bed. (Not to scale.)

Convolute Lamination

Convolute lamination (Figs 6 B and 9), common in the Porirua district, is usually situated near the middle of a graded bed and commonly along the transition between the greywacke and the argillite units. Occasionally it affects the whole bed. The thickness of the convoluted zone varies from 1 in. to 18 in. The maximum grain size in the convoluted zone, determined from four thin sections, is reasonably uniform, varying from 48μ to 58μ.

The shapes of convolutions range from gently undulating symmetric forms that are distinguishable from ripple marks only by the uneven distances between corrugations, to complex asymmetric contorted forms. Convolute laminae are seldom truncated by erosion in crests or troughs. In a bed the intensity of convolution gradually increases upward from greywacke to a maximum, and then decreases in the argillite. In the plane of bedding the convolutions have the appearance of small alternate oval domes and basins, as described by Kuenen (1953, p. 1056), ten Haaf (1956, p. 191), and Kingma (1958, p. 14).

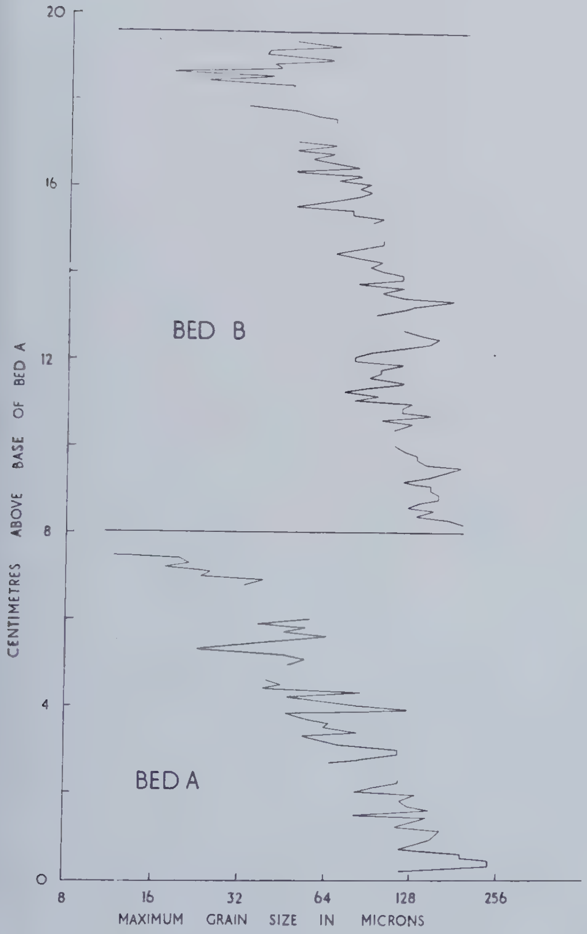

Fig. 7.—Variation in maximum grain size across two consecutive thin graded beds (A and B). Small gaps between successive thin sections shown by breaks in the line joining maximum grain size plots.

Current Ripple Marks and Cross Lamination

Current ripple marks are sparse and usually ill-defined in the Porirua district. In a single bed, they are slightly asymmetric with rounded crests and troughs, and have a constant wavelength (distance between crests) and amplitude. The wave length ranges from 7·5 cm to 25 cm, and the amplitude from 1·0 cm to 2·0 cm.

Kuenen (1950, p. 290) considered that a current flow of between 25 cm and 100 cm per second is required to develop ripples in sand and fine gravel. The sediments at Porirua are finer, and presumably required a current flow somewhat less than 25 cm per second.

Current ripple marks commonly occur in the same part of the bed as cross lamination. Prentice (1956) emphasized their genetic relationship by showing in a diagram, how cross lamination could develop by scour and fill from current rippling.

Cross lamination (Figs 6 C, 10, and 11) usually occurs within thin fine grained beds. Less frequently it occurs in the medial or upper parts (i.e. fine greywacke or argillite) of thicker beds. The thickness of cross lamination varies from 1·5 cm to 15 cm. Laterally the cross laminated part of an individual bed retains a uniform thickness as far as it can be traced. The maximum grain size of cross laminated sediments, as seen in thin sections, varies from 100μ to 60μ. The coarsest grains are from the thickest laminae.

Both cross and convolute lamination were seen in three beds. In one, cross lamination overlies convolute lamination, in the others the order is reversed.

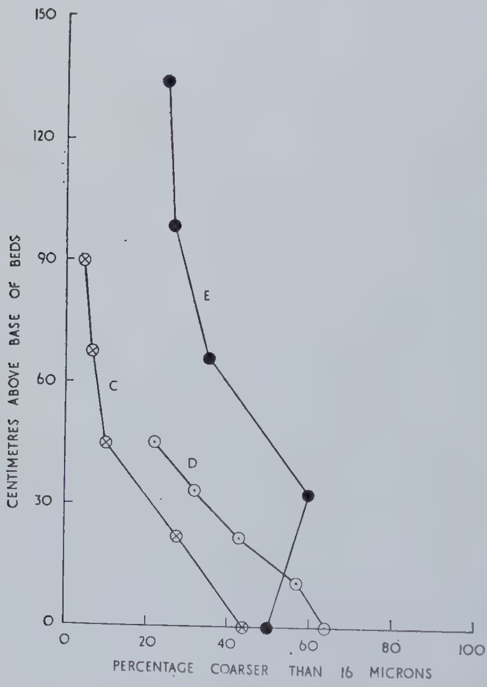

FIG. 8.—Relation of volume percentage coarser than 16μ grain size to the thickness of three individual beds (C, D, and E).

Mud Flakes

Mud flakes are angular to sub-rounded, elongated (or rarely curved), lenticular flakes or pellets from 0·1 cm to 20 cm long. They are usually only present in thick beds and are aligned subparallel or parallel to bedding. The flakes are largest and most abundant near the base of a bed (Fig. 6 E), but occasionally a bed exhibits successively smaller flakes grading upward. In two exposures small mud flakes were seen near the middle of a bed within coarse argillite.

Mud flakes were previously described in the Wellington Peninsula as intraformational conglomerates by Brodie (1953, p. 209) and Reed 1957, p. 30).

Current Markings

Two distinct types of current markings were observed on the base of a few graded beds, namely drag marks and flute casts.

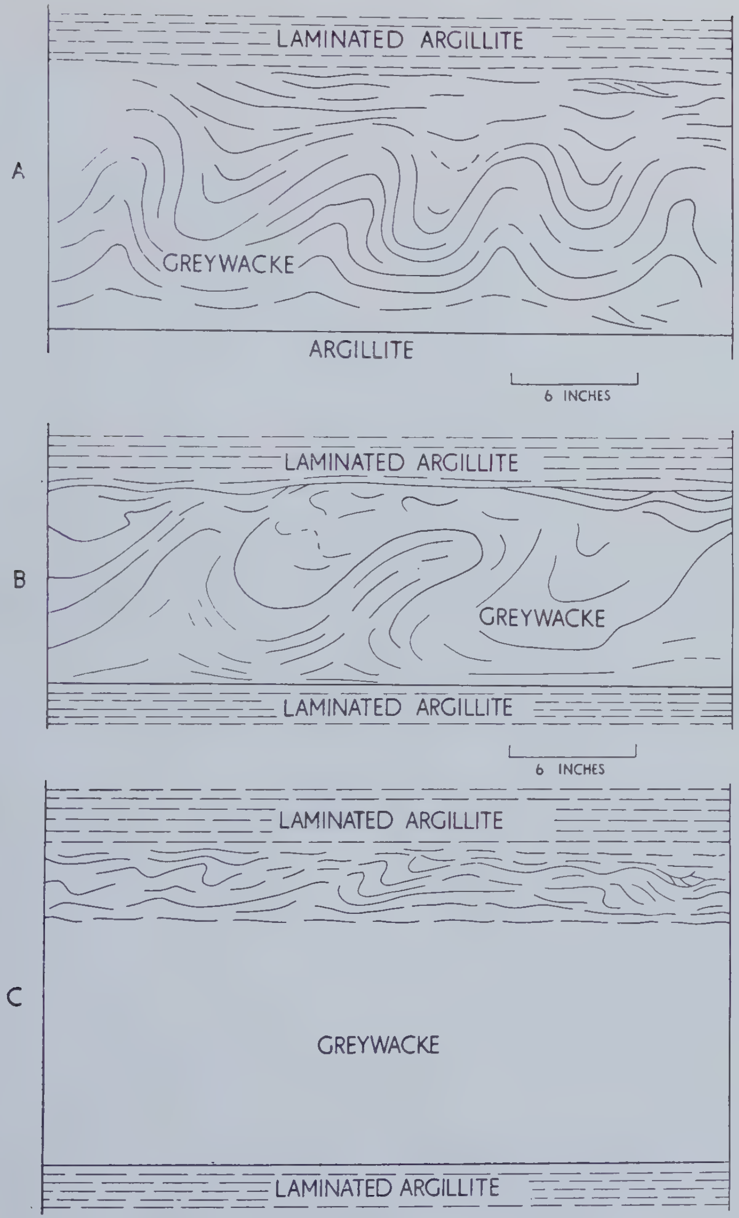

Fig. 9.—Convolute lamination in three beds (drawn from field sketches). A: large regular convolutions in the greywacke unit of a bed. B: large asymmetric convolutions with heeling crests, in the greywacke unit of a bed. C: small asymmetric convolutions in fine greywacke between greywacke and argillite units of a graded bed.

Drag Marks

Drag marks (Fig. 12), exposed along the coast south of Titahi Bay (N 160/383438), are straight, parallel to sub-parallel shallow ridges from 2 mm to 3 cm wide and up to 5 mm high, which represent infillings of grooves cut in the top of the underlying bed. They vary widely in cross-section, but individual drag marks retain the same section along their length.

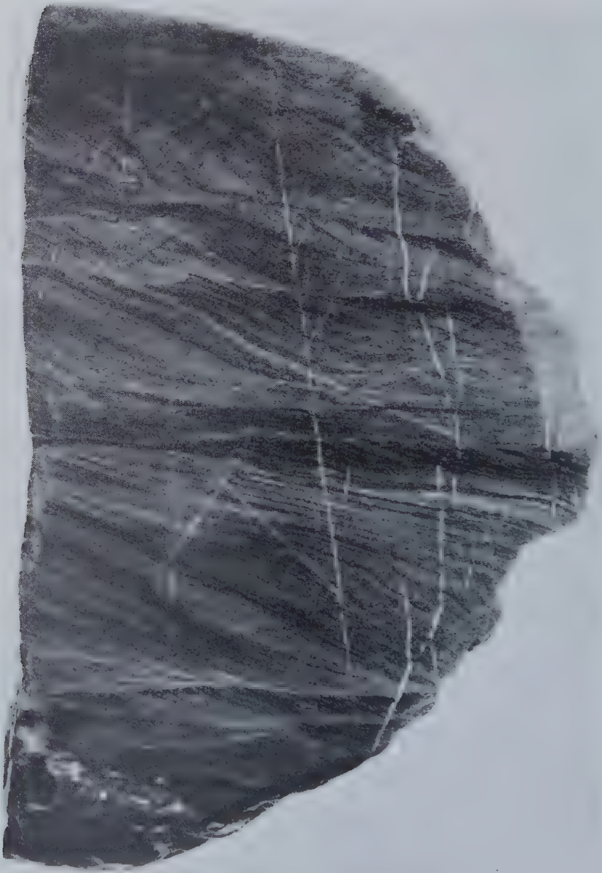

FIG. 10.—Cross lamination in fine greywacke. Current flow from left to right (×1).
—*M. D. King, photo*

Flute Casts

Small, aligned, tapering protuberances from 2 cm to 8 cm long and up to 3 cm wide were seen on the base of a few graded beds, and probably represent flute casts.

Bed Facing Criteria

The field criteria for determining bed facing in the Porirua district are, in order of decreasing importance: (1) graded bedding, (2) individual beds consisting of greywacke at the bottom, convolute zone in the middle and argillite at the top, (3) cross lamination, (4) mud flakes near the base of individual beds, and (5) current markings on the base of individual beds.

Directional-Current Structures

The original orientation of cross lamination and current markings was determined by the method of Kuenen and Sanders (1956, p. 656), modified to allow for the tectonic plunge at Porirua (Webby, 1959). The method was as follows:

A rectangular notebook was placed on the bedding plane with the long edge parallel to the plunging fold axis. A pencil was fastened to the notebook, parallel to the current structure to be measured. The notebook was rotated about the long edge parallel to the fold axis until its short edges were horizontal. Then the notebook was rotated to horizontal about a short edge, and a compass bearing was taken on the pencil alignment.

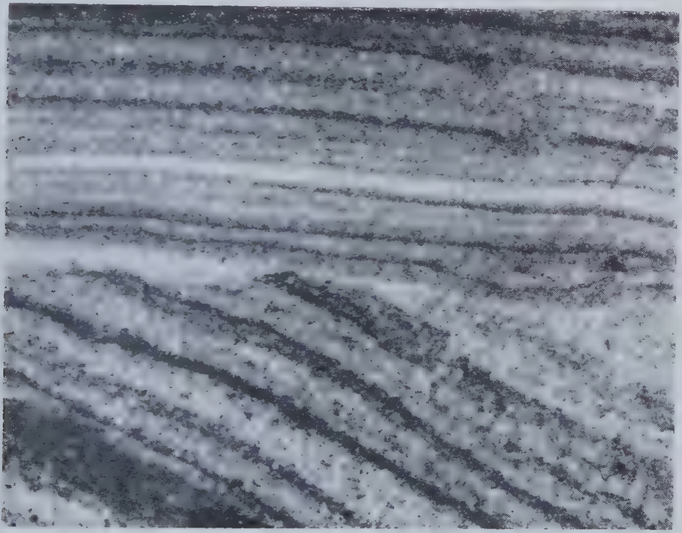

FIG. 11.—Detail of cross lamination, showing micro-grading of individual laminae and an abrupt contact between cross laminated and laminated units (× 5).
—*M. D. King, photo.*

Cross lamination is a good indicator of the general direction of current flow, accurate to about 45°. Eight observations of cross lamination indicate that currents flowed north to north-east (Table 1). The orientation of drag marks (3 observations) indicates a north-south current lineation, and the flute casts (3 observations), a north-north-east direction of current flow. More recently, the writer measured the orientation of current structures at ten additional localities in the Wellington Peninsula, and found that the north-north-east to north-east direction predominates.

Petrography

The rocks in the Porirua district are mainly greywackes and argillites. An arbitrary boundary of 0·06 mm grain size is selected to separate greywacke and argillite.

TABLE 1.—Current Orientations in Alternating Strata at Titahi Bay (N 160).

Sedimentary structure	Grid reference	Number of observations	Direction of current flow
Flute casts	388446	3	035°
Drag marks	382438	2	000°*
Drag marks	383438	1	007°*
Cross lamination	392449	4	010°–030°
Cross lamination	388446	2	020°–045°
Cross lamination	386436	2	000°–020°

*The sense of current direction could not be determined from drag marks, and from the flute cast and cross-lamination directions is inferred to be 000° and 007° rather than 180° and 187°.

TABLE 2.—Modal analyses of three greywacke samples.

Sample No.	1	2	3
Quartz	21·4	32·9	43·4
Total feldspar (potash feldspar in brackets)	13·0 (5·6)	21·2 (7·7)	26·8 (8·0)
Biotite, muscovite, and accessories	7·5	5·3	1·3
Fine matrix	50·7	33·3	22·9
Rock fragments	7·2	7·3	5·6
Total	99·8	100·0	100·0
Number of counts (from automatic point counter)	1407	919	1032

1. Sample from the base of a graded bed, south of Titahi Bay (N 160/383438).
2. Sample from the base of a graded bed, north of Titahi Bay (N 160/390448).
3. Coarse grained sample from a composite graded bed, north of Titahi Bay (N 160/392449).

GREYWACKE

Microscopic examination of representative greywackes reveals angular, poorly sorted clastic grains embedded in a slightly chloritized and sericitised clay matrix (Fig. 13). The clastic grains and matrix are not well differentiated, but to facilitate description an arbitrary value of 16μ is taken as the lower limit for clastic grains.

The clastic grains are quartz, feldspar, rock fragments, and biotite. Quartz grains form between 21% and 43% of the rock volume (Table 2). They commonly display undulose extinction and not infrequently contain inclusions.

Both potash and plagioclase feldspars are present in the rocks. Potash feldspars are orthoclase and less plentiful microline. Orthoclase is

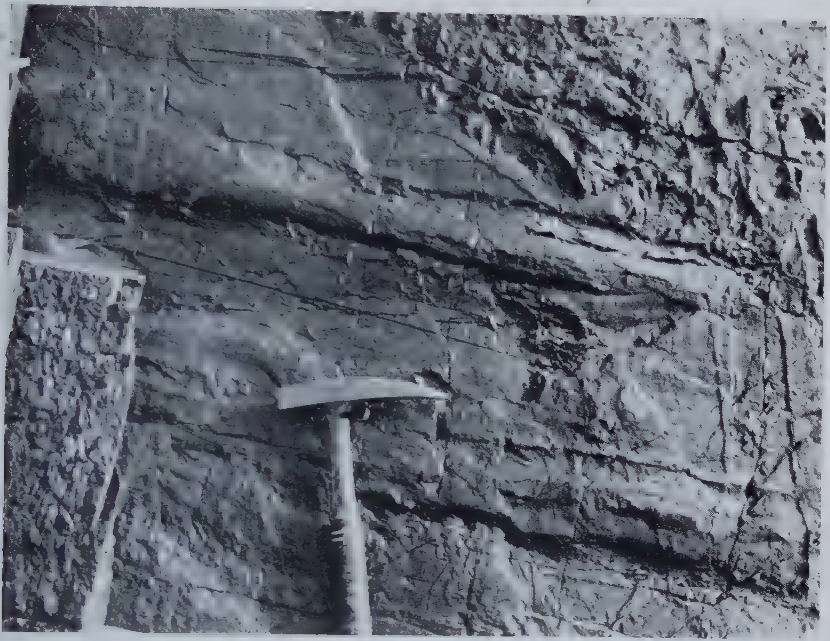

FIG. 12.—Large and small sub-parallel aligned drag marks on the base of a bed. Note the worm tracks between the hammer head and the large drag mark in the upper part of the photograph.

usually cloudy or less commonly clear. Occasionaly orthoclase exhibits Carlsbad twinning. Plagioclase feldspar is twinned or untwinned, the former being more common. Numerous extinction angle measurements of twinned plagioclases indicate a general range from oligoclase to andesine (An 25 to 40). Perthite also occurs. Table 2 shows that feldspar varies from 13% to 25% in the three greywacke modal analyses. By a staining technique (Chayes, 1952) potash feldspar was calculated as representing 30% to 45% of the total feldspar. Intergrowths of quartz and feldspar are recognized, and include graphic and myrmekitic forms.

Flakes of biotite form less than 6% of the rocks. Sericite was also observed. Rock fragments, present in varying amounts up to 7%, are fine grained siltstones and mudstones, and possibly hornfels. The matrix forms 23% to 50% of the volume in the three samples analysed (Table 2).

Accessory minerals, observed in thin sections, are muscovite, sphene (including twinned varieties), epidote, pink garnet, and zircon. None of these minerals appears to be authigenic.

A heavy mineral separation was prepared from sample 1 (Table 2). The heavy minerals in the 125μ to 250μ size range represent 1·5% by weight of the total sample. The dominant heavy mineral is biotite.

Garnet (pink variety often with tiny globular inclusions some of which may be zircon), sphene, epidote, chlorite, zircon, and iron ore are less abundant. Apatite and rutile are rare. Microscopic observations indicate that the most abundant and varied heavy mineral assemblages are in greywacke that contains a high percentage of matrix.

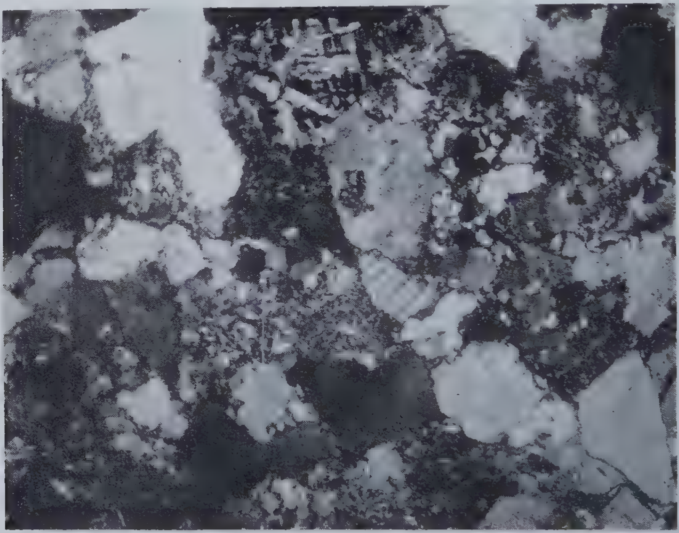

FIG. 13.—Photomicrograph of greywacke from north of Titahi Bay (Table 2, sample 3), showing the angularity of clastic grains and poor sorting. Note the clastic grains of quartz, plagioclase feldspar, orthoclase, and microline set in a fine grained matrix. Polarised light, × 58.

—*R. H. Clark, photo.*

The Porirua greywackes ("Alpine Facies" of Wellman, 1952) were compared with a greywacke sample collected from Puoroan strata at South Head, Port Waikato (N 51/235941) ("Hokonui Facies" of Wellman, 1952). The Port Waikato greywacke has: (1) a much higher percentage of rock fragments that are mainly volcanic, (2) more feldspar, a greater proportion being plagioclase, (3) less quartz, and (4) some detrital calcite.

ARGILLITE

In texture the argillites are fine grained equivalents of greywackes, with a larger percentage of fine matrix. Reed (1957, p. 27) indicated that in chemical composition the argillites differ from greywackes in having a lower silica content, a higher alumina content, and in being potassic rather than sodic.

RADIOLARIAN JASPER

Radiolarian jasper fragments, from a Pleistocene solifluction deposit (N 160/413394), are pale red in colour. They consist of cryptocrystalline quartz and a small amount of finely disseminated hematite.

Paleontology

Tubes of *Terebellina* (*Torlessia*) *mackayi* (Bather) were found in place on the coastal strip north-east of Mt Cooper (N 160 402458), and from a large locally derived boulder immediately north of Titahi Bay (N 160/388448). *Terebellina* (*Torlessia*) *mackayi* may indicate a Triassic or Lower Jurassic age (Bather, 1906; Jaworski, 1915) for the rocks of the Porirua district.

Titahia corrugata, an annelid described by Webby (1958), was found throughout a 250 ft thick overturned sequence at Rock Point. The sequence is composed of thin beds underlain by a few thick beds. *T. corrugata* is confined to the argillite unit of a bed, and particularly near the abrupt contact with the greywacke unit of the overlying bed.

Worm tracks were observed in association with drag marks on the base of one graded bed (Fig. 12), south of Titahi Bay (N 160/382440).

Crawford (1869) and McKay (1888) reported plant remains in the rocks on the shores of Porirua Harbour. Although no plant remains were found, just south of Paremata (N 160/417435) an unusual argillite contains fine, dark, aligned mudstone fragments which are slightly carbonaceous.

The red jasper fragments contain imperfectly preserved Radiolaria (Spumellaria variety) with diameters of 90μ to 180μ.

INTERPRETATION

The alternating greywacke and argillite strata of the Porirua district belong to a "marine geosynclinal association" (Reed, 1957), and are a part of the "Alpine Facies" deposited along and to the east of the axis of the New Zealand Geosyncline (Wellman, 1956).

Two recent hypotheses have been suggested to explain the origin of alternating strata in geosynclines and "geosynclinettes" (Kingma, 1958, p. 24): the redeposition theory by turbidity currents (Kuenen and Migliorini, 1950), and the basin and bar theory (Kingma, *loc. cit.*). Although Kingma's theory explains the mode of deposition in a "geosynclinette", it does not satisfactorily account for the mode of deposition of thick and extensive alternating strata of the New Zealand Geosyncline. It depends on a fine adjustment between depth and bar conditions, but such an adjustment is unlikely to be maintained in time and place in a geosyncline. In contrast, turbidity currents can be expected over a wide range of conditions in both geosynclines and "geosynclinettes". As the theory of redeposition by turbidity currents is in accord with all the known facts, it has been adopted by the writer as the preferred hypothesis for the origin of the alternating strata in the Porirua district.

Origin of the Sedimentary Features

Kuenen and Migliorini (1950, p. 91) invoked that "turbidity currents of high density . . . supplied the sediment and deposited it in graded beds". Well *graded beds* (Fig. 7, bed A) are deposited from turbidity currents charged with an even range of grain sizes. More commonly, beds are non-graded in their lower parts and well graded in their upper parts (Figs 4 and 6 A). These beds may be formed from turbidity currents charged with similar coarse grains and an even range of finer grains.

Two types of composite graded bed are recognized. One type consists of a thick primary bed overlain by thin, and on the average finer secondary and tertiary beds (Fig. 6 D). It probably originated by a turbidity current flowing along the sea floor, splitting into a large high density primary suspension and slower moving less dense secondary and tertiary suspensions. The other type of composite graded bed is produced when a turbidity current creates unstable conditions at its point of origin, and a second turbidity current is generated which follows and plunges beneath the tail of the first (Kuenen and Menard, 1952, p. 92). This results in a composite bed composed of a primary bed truncated by a well graded secondary bed (Fig. 6 F).

Kuenen (1953, p. 1050) interpreted *lamination, current ripple marks*, and *cross lamination* as the product of traction accompanied by sorting, of a load along the bottom in a turbidity current. Alternatively, lamination and cross lamination may be formed by wave-like pulsations in a turbidity current as suggested by Hills and Thomas (1954, p. 127).

Innumerable hypotheses attempt to explain the origin of *convolute lamination*. Ten Haaf (1956) reviewed the various theories of origin, and suggested that "most of the characteristic properties of convolute lamination can be accounted for by the general hypothesis that in a growing hydroplastic bed, slight differential forces—probably in most cases current rippling as suggested by Kuenen—can effect a corrugation of the laminae which grows into exaggerated forms after being buried, both by accelerated deposition in the troughs and expulsion of excess water through the crests" (p. 194).

Mud flakes include angular and curved forms which were clearly plastic when deposited. Only the cushioning effect of a turbid suspension satisfactorily explains the transportation and deposition of unconsolidated mud flakes. Brodie (1953, p. 209) stated that fragments were not transported far and can sometimes be seen in the process of disruption. Short transport may apply in many instances, but where large flakes grade up into smaller flakes within a graded bed longer transport is implied, enabling sorting of the suspended mud flakes in the turbidity current.

Drag marks (groove casts) are interpreted by Prentice (1956, pp. 43–45) as infillings of parallel striations which appear to have been cut into the surface of the mud below, by sharply pointed fragments dragged along by a turbidity current. Kuenen (1957a, p. 241) considered that *flute casts* were formed by scouring of the underlying mud by a sediment-laden turbidity current.

The comparative rareness of current markings is almost certainly due to the bedding plane faulting that is associated with strong folding of the Porirua rocks.

Provenance and Dispersal

Reed (1957) stated that the greywackes and argillites were derived "from a plutonic terrain of granite, gneiss, and metamorphic rocks, the erosion of which was marked by little chemical decomposition; rapid or short transport as indicated by the angularity of the clastic grains; and rapid deposition as implied by the poor sorting of the rocks". This statement is consistent with the evidence assembled in the present study.

The fact that the north-north-east direction of current flow at Porirua is sub-parallel to the tectonic trend suggests that the turbidity currents transported sediment along the axial belt of the geosynclinal trough. Kuenen (1957b) cited numerous overseas examples of depositional current directions coinciding with tectonic trends.

Depositional Environment

The freshness of the feldspar indicates predominantly rapid mechanical disintegration of the Lower Mesozoic landmass. With such rapid mechanical erosion it is probable that a great quantity of coarse material would accumulate immediately offshore. In contrast, fine material (Porirua greywacke less than 0·5 mm maximum grain size) would be deposited a considerable distance from this landmass, and because a continuous bottom slope is required for the transportation of sediment (whether by turbid suspension or traction), deposition is necessarily in deep water. A deep-water origin is supported by graded bedding and the absence of features typical of shallow water deposition.

A notable absence of benthonic faunas, apart from annelids, suggests an unfavourable environment for bottom dwellers, perhaps due to the combined effect of deep water, poor circulation, and the turbidity current mode of deposition.

ACKNOWLEDGEMENTS

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PLEISTOCENE AND RECENT STUDIES OF WAITEMATA HARBOUR

PART 3—TAMAKI HEAD TO MECHANICS BAY

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(Received for publication, 4 March 1959)

Summary

Low-level terraces built in bayheads along the eastern portion of the south coast of Waitemata Harbour are ascribed to sedimentation during Recent regimes of high sea-level. Submerged and infilled valleys of streams tributary to the ancestral Waitemata River are described.

INTRODUCTION

The southern shore of Waitemata Harbour, eastward from the city of Auckland to Tamaki West Head, appears at first sight to be a straight, simple coast, marked over much of its length by cliffs rising steeply to the dissected surface of the 100 ft terrace which is strikingly developed in this area. The semblance of straightness exhibited by this coast is due, in part, to the considerable reclamation that has been effected near the city itself, with the result that the many small bays—St Georges Bay, Mechanics Bay, Wynyard Bay, Commercial Bay, and Freemans Bay—which formerly characterized the foreshore of the embryo city, have been completely eliminated. The effect is enhanced by the construction of a coastal road, Tamaki Drive, which cuts across Judges Bay and the wide, sprawling inlet of Hobson Bay, and thence skirts the coast from Hobson Point to Achilles Point, hugging the foot of the cliffs on the headlands and striking across the intervening bayheads.

Cliff recession has been considerable east of Hobson Bay, where the coast lies outside the shelter from offshore winds afforded by the Devonport Peninsule, and was unprotected from north-easterly storms until the development of the mass of youthful Rangitoto Island. Offshore waters are shoal, and the shallow platform is studded with rocky reefs extending out from the shore for more than a mile. No investigatory work, other than sounding, has as yet been attempted over this area of shelf, but the distribution of rock reefs makes it seem not unlikely that they are relics of former extensions of prominent headlands on the coast. Thus the East Bastion Reef would appear to be a seaward continuation of the ridge ending in Gowers Point, and the West Bastion Reef and Bean Rocks a prolongation of the divide between Mission Bay and Kohimaramara. The reefs may thus indicate the former extent of earlier divides, and delimit ancient extensive

N.Z. J. Geol. Geophys. 2 : 479-88.

valley systems related to a lower base level than now obtains, and comparable in size and form with other valleys eroded in glacial times and preserved in the sheltered waters on the North Shore side of the harbour (Searle, 1959). Evidence to support this hypothesis is available in the sub-surface features of all of the bayheads along the coast and will be presented below. The suggested reconstruction of these ancient divides and the probable lie of the old valleys, tributary to the ancestral Waitemata River, is shown in the locality map, Fig. 1.

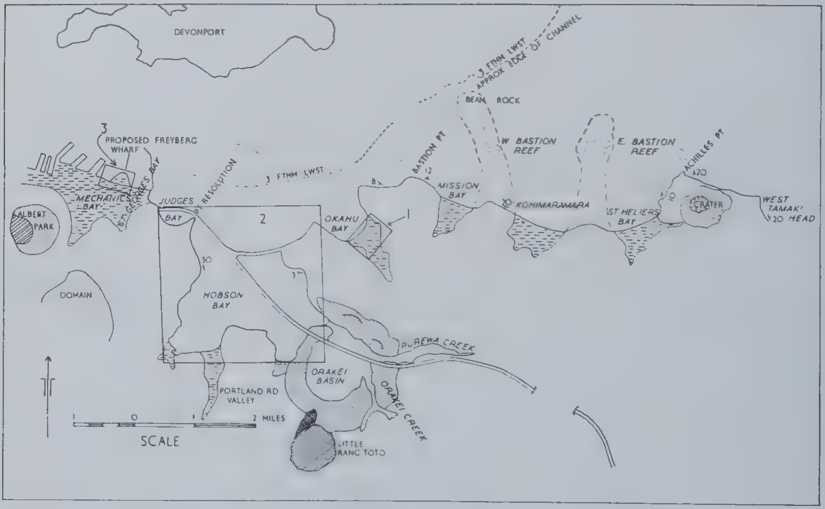

FIG. 1.—The Waitemata coast between Tamaki Head and Mechanics Bay, showing localities of 1 (Fig. 3); 2 (Fig. 5); 3 (Fig. 7). Low terraces of Recent sediments, broken lines; tuff accumulation, dotted; scoria, ruled diagonally; basalt, cross-ruled.

This coastal section, which was a source of much interest to early geologists, has recently been closely examined by Professor A. R. Lillie. His mapping (map lodged in the Department of Geology, University of Auckland) reveals a bewildering variation in the strike and dip of beds. The general impression given is of an incompetent mass of strata rucked into a series of rolling folds, or of a body of substantially horizontal strata broken and complexly folded by delta slumping. On the whole, the latter picture is more satisfying to the writer. Headlands and reefs alike owe their preservation against erosion to the outcropping of the resistant andesitic grit members known as Parnell Grit.

Volcanic eruptions have occurred at several points near the present coast, but these outbursts have been predominantly phreatic in nature and have produced no large lava flows to buttress the coast line in the way that flows have protected the exposed coast of the North Shore (Searle, 1959). At Achilles Point, a small centre of eruption lies almost on the edge of the cliff line and has formed a circular crater, 25 chains in diameter, surrounded by a tuff ring, the remnants of which now stand about 50 ft above the surface of Waitemata Formation rocks on which the ring was built. Marine erosion has caused the cliff line to recede to intersect the northern rim of the crater, and here most of the ejectmenta has been removed. On the north-western flank of the cone, subaerial erosion has stripped the volcanic debris from the steep slopes of the underlying Tertiary strata. On the eastern side, however, the rim still stands high, so that where it meets the coast the upper portion of the cliff is of bedded tuffs which, through undermining, have shed a mantle of tuffaceous blocks extending down to the beach beneath. The extent of erosion on this cone suggests that its formation was moderately early in the sequence of activity in the Auckland volcanic field, which is known to extend over more than 40,000 years. Hence, it must be regarded as most unlikely that this vlcano erupted on the edge of the sea, but rather, because of prevailing low sea-levels, that the coast was some, perhaps many, miles distant from the vent at the time of the eruption.

A further phreatic eruption occurred in the lowlying area at the eastern head of Hobson Bay and formed the crater, half a mile in width, now occupied by Orakei Basin. On the north-eastern side, ejectmenta was plastered up against the Tertiary highland and piled up on its surface to an elevation of 150 ft. The Purewa and Orakei creeks were dammed, but the absence of any conspicuous terraces upstream from the volcano indicates that the streams were able to quickly form a passage through the blockage and thus establish through drainage on the northern side of the cone along the line of contact of the volcanic deposits and the underlying Tertiary rock surface. Subsequent rise in sea-level permitted ingress of tidal waters through the breach, as well as the accumulation in the crater of marine muds which now fill it almost to mean sea-level.

Erosion has been extensive both within the Orakei crater and on the outside of the ring, with the result that a large part of the eastern wall, facing Hobson Bay, has been worn away, lowering the rim to 50 ft above mean sea-level. On the inside, steep cliffs have been formed and eroded back so far as to expose the basement of Waitemata strata on which the tuff rests at about 8 ft above mean sea-level. The Tertiary strata are not exposed outside the ring on the shore platform of Hobson Bay or in the breach in the ring, so it seems that the volcanic pile buried a low spur of Waitemata sandstone that extended out from the Remuera Tertiary ridge into the Purewa-Orakei valley. On the northern side, where tuff was deposited on the higher and steeper wall of this old valley, large-scale slumping due to the sliding of the tuff on the clays of the buried surface has produced conspicuous crescentic slump scarps. The products of other volcanoes close to this section of coast do not extend sufficiently far towards the harbour to have exerted any effect on coastal morphology.

Low Terraces

As has been suggested, the coastal strip, eastwards from Hobson Point, consists of faceted divides forming cliffed headlands, separated by crescentic beaches developed in intervening valleys. These beaches are all backed by more or less extensive flats (see Fig. 1) at an elevation of 10 ft to 12 ft above mean sea-level, which appear to occupy the heads of valleys excavated in the 100 ft to 120 ft terrace cut across the Waitemata terrain. At St Heliers Bay, Kohimaramara, and Mission Bay, the flats extend back from the beaches for distances of approximately 20 chains, and are enclosed by steep, sometimes cliffed, valley walls. They are built features and are regarded as bayhead fills of Recent sediments laid down at the time of post-glacial maximum sea-level.

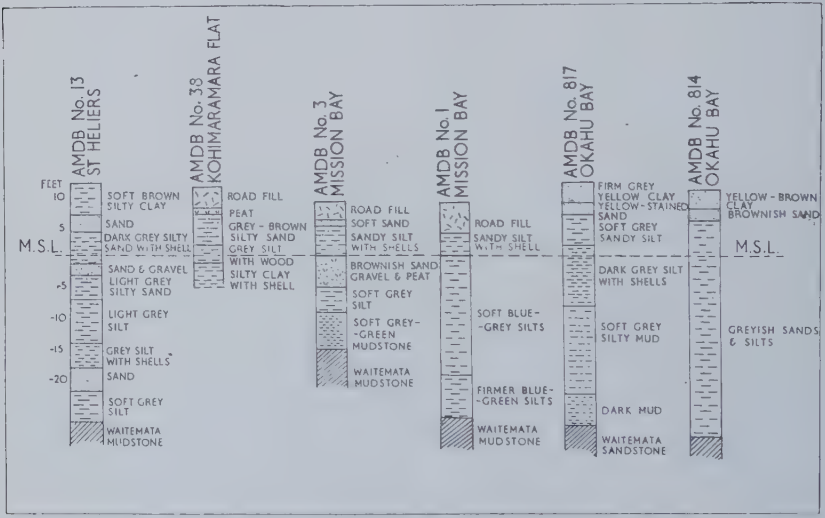

Fig. 2.—Sections constructed from bore logs of holes drilled through low terraces.

Few data are available concerning the constitution of the low terrace at St Heliers Bay. A bore sunk by the Auckland Metropolitan Drainage Board in 1951, at the south-west corner of the recreation reserve,, 12 chains distant from the beach, passed through marine silts and sands, at some levels with abundant shell. It pentrated the underlying Waitemata formation at a depth of 27 ft below mean sea-level (AMDB bore No. 13—see log, Fig. 2). The terrace here is much restricted in width and runs southward as a narrow tongue up the small valley draining Dingle Dell. AMDB bore No. 10, 6 chains farther up the valley, at the corner of Parau Street, encountered the basement at 12 ft below mean sea-level. It wil be noted that these bores are located near the back of the terrace and sited not necessarily on the line of ancient drainage, so that they give indication only of minimum depth of fill in the buried valley. They show clearly, however, that the terrace is a built feature, that it is constituted of marine sediments to a height of 12 ft above mean sea-level, and that it occupies a valley floor of moderate gradient cut well below the level of control of modern seas.

Hochstetter and Peterman's map of the Auckland isthmus (Hochstetter, 1864) shows the flat behind the beach at Kohimaramara as a swamp. After easterly gales have stripped sand from the beach, a number of logs are exposed in a rusty-brown sandy silt which contains impressions of leaves. Such material is consistent with a swampy fill. Only a few post-hole borer and auger holes have been put down to shallow depth below the surface of the flat at approximately 10 ft above mean sea-level. AMDB bore No. 38 (Fig. 2) and others to just below mean sea-level show silts with shells at about that datum. The depth of the fill is not known, but it is probable that it conforms with the pattern established in the other similar deposits described in this article.

At Mission Bay, the only data available are from bores put down in Tagalad Road, parallel with the beach and 18 chains at the head of the flat. In the latter locality, where the surface is 11 ft to 12 ft above mean sea-level, the basement of Waitemata Formation was entered at 4 ft above mean sea-level, at Tagalad Road it was encountered at 15 ft below mean sea-level at the eastern end and 26 ft below mean sea-level at the western end. The logs (Fig. 2) show the terrace as underlain by soft, grey, and darkish silts and sands with shell in members at about the datum level. The old valley floor covered by these silts seems to be more deeply entrenched on its western side where the hill slopes rise abruptly from the surface of the terrace.

There is a similar terrace behind the beach at Okahu Bay, extending back as a narrow tongue for half a mile. The Drainage Board has recently sunk a number of bores along proposed sewer lines across this flat, and at a proposed pumping station near its eastern margin. The holes on the line AB of Fig. 3 were by post-hole borer and penetrated only to depths of 8 ft to 12 ft below the surface. All were in Recent fill and in no case was the base of these young sediments reached. The line EF skirted the westerly edge of the flat and then crossed it at a small angle some 1,200 ft back from the present shore line. Bores on this line all penetrated the basement, and a section (Fig. 4) established on their logs shows a V-shaped valley with a depth of 40 ft below mean sea-level. Sections from two bore logs, AMDB Nos 814 and 817, are given in Fig. 2. It will be noticed that the fill is wholly of marine sediments, muddy silts, and sands with much shell; in the lamellibranchs both vaves are commonly present and the shells are closed. Samples at present await radiocarbon dating.

For these Recent sediments that underlie terraces at 10 ft to 12 ft above mean sea-level in this district the name Okahu Formation is proposed. The type area is defined as Okahu Bay (N 42/337604), the type section, of which the upper part is shown by AMDB borehole No. 817, to include all sediments underlying the surface of the terrace and deposited during the Flandrian rise in sea-level.

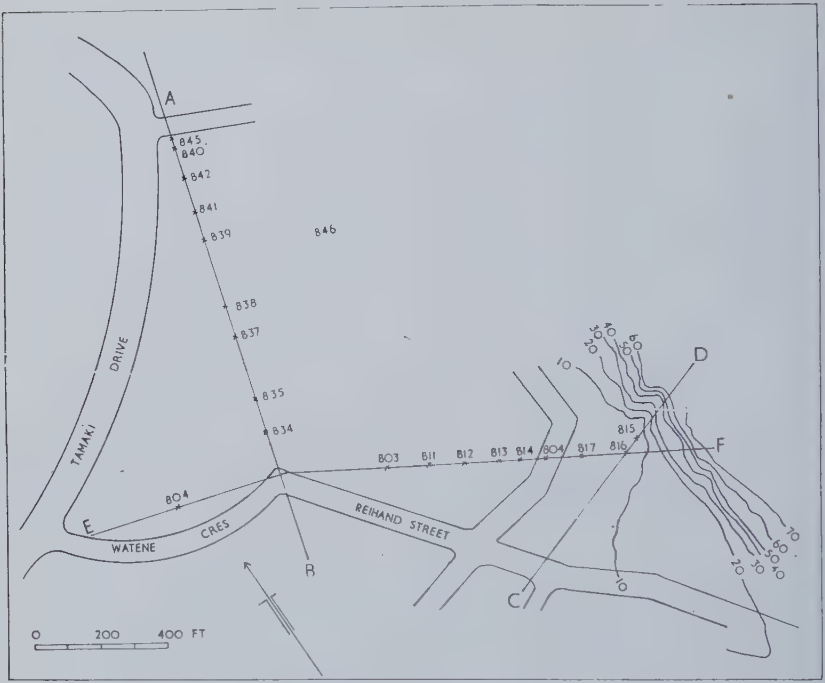

FIG. 3.—Locality map, Okahu Bay.

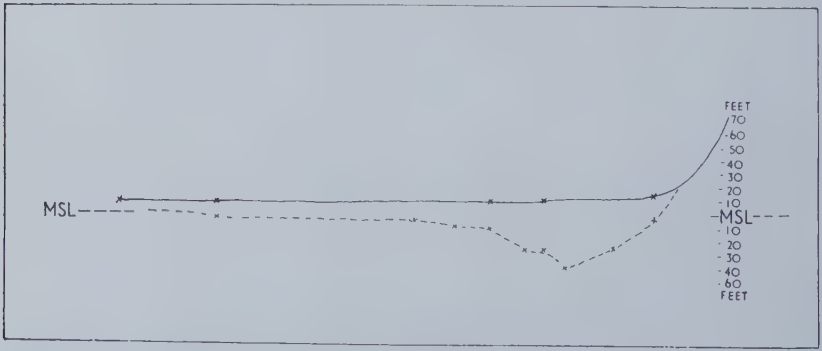

FIG. 4.—Section on the line EF, Fig. 3. The broken line represents the buried surface of the Waitemata Formation.

WESTERN SECTION

Hobson Bay has been explored, for proposed reclamation, by a closely-spaced grid of boreholes put down by the Ministry of Works. Data are also available from the Auckland Metropolitan Drainage

Board, whose main sewer crosses the inlet, and from the Auckland Harbour Board from a survey along the line of Tamaki Drive. Figure 5, based on the Ministry of Works plan A.D.O. 27624, shows contours established on the surface of the Waitemata sediments that floor the bay, and the section, Fig. 6, is located on the line of the sewer. The contours suggest a continuation of the Victorian Avenue headland as a rounded divide separating two ancient, deeply-entrenched drainage channels. The easterly channel formerly carried the water from the Purewa-Orakei creek catchment area and was particularly steeply walled on the Orakei side.

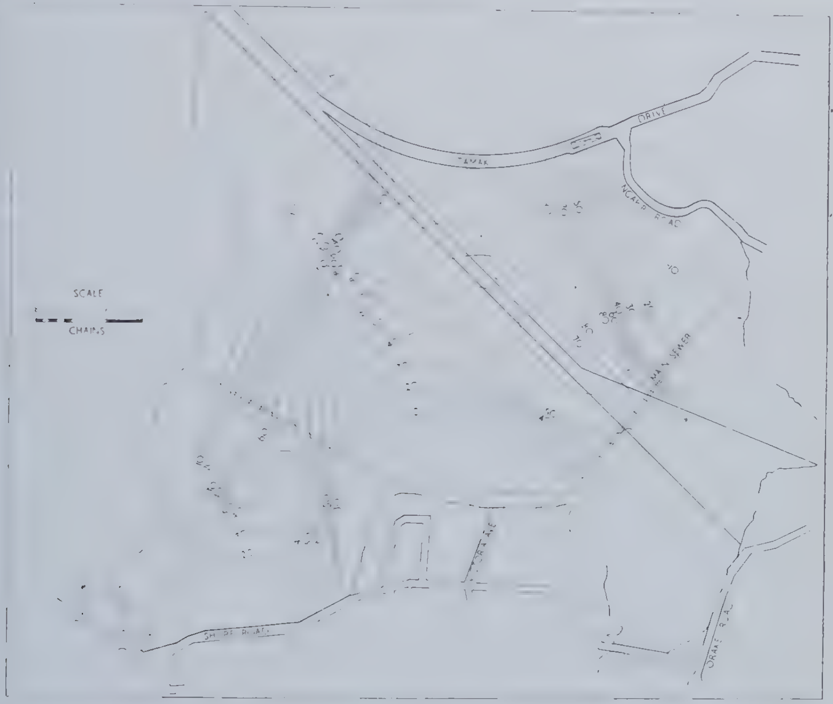

FIG. 5.—Contours in Hobson Bay (in feet below mean sea-level) on the buried surface of the Waitemata Formation (Estab'ished on bores by Ministry of Works, modified by data from Auckland Harbour Board and Auckland Metropolitan Drainage Board. After M.O.W. plan ADO 27624.)

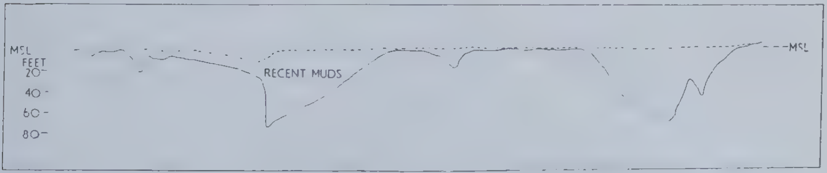

FIG. 6.—Section on the line of sewer across Hobson Bay, showing surface of Recent muds (broken line) and of buried Waitemata Formation (solid line). (Horizontal scale: 1 in. = 250 ft)

On the western side of the bay, the old waterway bifurcated with one branch draining the Portland Road valley and a part of Remuera, whilst the other collected water from the steep valleys between Parnell and Newmarket. No terrace equivalent to those described earlier is apparent in the bayhead, and it is possible that tidal flow from the long inlet, together with surface discharge from the moderately large watershed, were sufficient to retard sedimentation and prevent terrace building. As may be seen from Fig. 5, these ancient valleys were downcut to a depth of 90 ft below mean sea-level beneath Tamaki Drive, with a fall from Shore Road of only about 1/130. From Tamaki Drive to its inferred junction with the valley floor of the ancestral Waitemata stream, the fall would be only a further 20 ft. Hence it may be concluded that these small tributaries were well adjusted to their controlling base levels.

The valley of the ancient Purewa-Orakei stream in particular is narrowly confined and the contours crowd as the tuff cone is approached. Bearing in mind the exposure of Waitemata sandstone above sea-level in the inside of the crater, it seems highly likely that the streams descended in a fall or rapid into the floor of the bay. Borings on the eastern side of the Victoria Avenue headland show that the tuff cone extended across almost to the Tertiary promontory.

Scoriaceous basalt pebbles and tuffaceous grits were also recorded in the logs of bores from the western side of the Victoria Avenue headland. For example, Bore No. 8 on the Ministry of Works site plan, situated near Shore Road, passed through 50 ft of Recent mud fill and then encountered 9 ft of muddy tuffaceous grit, with pebbles of basalt 2 in. in diameter, resting on Waitemata sediments at 60 ft below mean sea-level. In other bores, volcanic debris was also recovered and always at the base of the fill. Whilst it is true that the small streams feeding this valley drain the flanks of other volcanoes, it seems to be most probable that this basaltic material originated in the Orakei Basin eruptions. If this is so, then it would be reasonable to assume that activity at this centre must date back to a time when the Flandrian rise of sea-level had attained a height approximately equivalent to 60 ft below present mean sea-level.

Some of the silts from deeper levels near the mouth of the bay were lighter in colour and more compact than those from nearer the surface. However, none of the sediments had lithological properties that were convincingly like those typical of the Pleistocene Whau Formation which forms the lower part of the fill in the ancient valleys of Shoal Bay and in the upper reaches of the harbour. Without evidence to the contrary, it is preferred to regard change in colour and compactness as a function of depth and time of burial, and to consider the whole mass of sediments in the fill as the product of a single continuous episode of deposition.

Since 1854, reclamation of coastal fringes west of Hobson Bay has been the continuing policy of local authorities. St Georges Bay and Mechanics Bay have now for many years been reclaimed far beyond their former headlands, and it is only with difficulty by following the

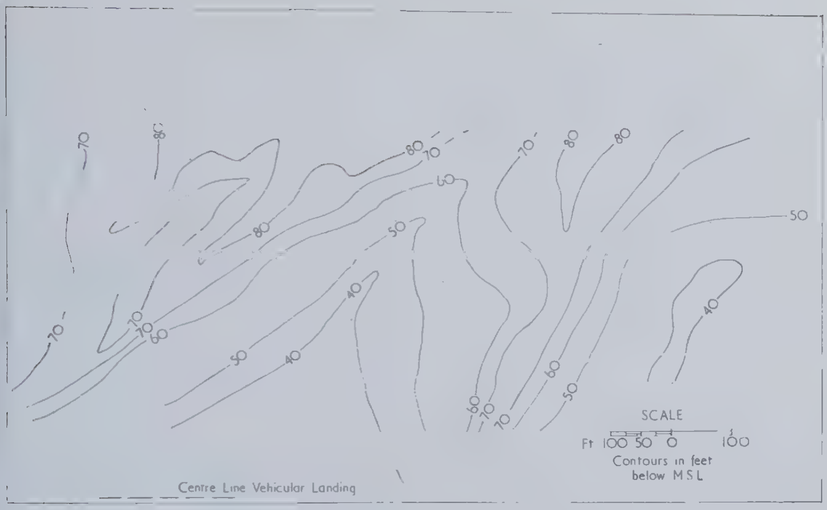

FIG. 7.—Contours, in feet below mean sea-level, established on Waitemata Formation below the Recent silts of Mechanics Bay.

former cliff line that the natural coast may be reconstructed. No data are available regarding depth of original sediments in these inlets or of the configuration of their hard rock bottoms. Evidence that they, too, were infilled valley bottoms of an earlier cycle is, however, afforded by the exploratory drilling programme carried out by the Auckland Harbour Board in preparation for the construction of the proposed Freyberg wharf. From a grid of 150 bores to the Waitemata sediments beneath the harbour muds, the Board's engineers were enabled to draw the contours of the rock bottom shown in Fig. 7. The present harbour bed over this sector is a smooth flat at approximately 30 ft below mean sea-level. The old floor is very different. Two channels cut to a depth of 80 ft below mean sea-level are separated by a broad spur plunging from a level of about 50 ft below mean sea-level. The two drainage channels may readily be identified as the extension of prominent deep valleys on the isthmus—a small stream originally discharging into St Georges Bay on the east, and a larger one draining Grafton Gully on the west. The bore logs are very similar to those obtained from Hobson Bay. Close examination of typical core samples from the fill indicates that all the material is Recent in age. Typical logs read as folows:

A.H.B. bore A13 (to bottom of channel):

Mean sea-level to 26 ft below mean sea-level	water
Mean sea-level to 40 ft below mean sea-level	dark silts
Mean sea-level to 49 ft below mean sea-level	yellowish-grey fine silt
Mean sea-level to 80 ft below mean sea-level	soft, light grey silts

Waitemata Formation

A.H.B. bore C7 (to top of divide):

Mean sea-level to 22 ft below mean sea-level	water
Mean sea-level to 28 ft below mean sea-level	silts (dark)
Mean sea-level to 36 ft below mean sea-level	sand and shell
Mean sea-level to 38 ft below mean sea-level	friable grey clay
Mean sea-level to 41 ft below mean sea-level	greyish silt
Mean sea-level to 48 ft below mean sea-level	soft silty sand

Waitemata Formation

In this paper, it has been shown that along the section of coast described, the major topographical features of the land extend beyond the coastline and find expression on the solid floor offshore. Every large valley system has a seaward extension with about the same order of relief as is shown on the land area. The submerged and buried valleys are inferred to be tributaries to an ancestral Waitemata River of glacial times and to have been infilled with sediments by rising seas during the Flandrian transgression in the Recent epoch. Extensive terraces were built at 10 ft to 12 ft above mean sea-level, but there is no indication that similar terraces were built in the bays near the city. Neither is there any evidence of any earlier infill during previous warm intervals during the Ice Age.

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A NEW SPECIES OF *MACCOYELLA* FROM RAUKUMARA PENINSULA, WITH A REVISION OF *M. MAGNATA* MARWICK

By J. B. Waterhouse, New Zealand Geological Survey, Department of Scientific and Industrial Research

(Received for publication, 7 April 1959)

Summary

Maccoyella incurvata n.sp. is described from Upper Jurassic or Lower Cretaceous rocks near Kahikatea Settlement, Opotiki district, Raukumara Peninsula. *M. magnata* Marwick is re-examined, and considered to be possibly identical with *M. reflecta* (Moore).

Introduction

In 1955, Dr H. W. Wellman, now at Victoria University of Wellington, discovered numerous specimens of a lamellibranch species in Sheet N78, fossil locality No. 508 (GS 6292). Further specimens were collected in 1956 by Mr G. W. Grindley, New Zealand Geological Survey. They occur in a compacted mudstone at the south end of Kahunui Stream, a tributary of the Waiotahi River, near Kahikatea Settlement, Poverty Bay. The specimens have been identified as a new species of *Maccoyella*. This is the second known occurrence of *Maccoyella* in New Zealand. The first record is by Marwick (1939), also from the Raukumara Peninsula.

Systematics

Genus **Maccoyella** Etheridge, 1892

Type Species: (By original designation Etheridge, 1892) *Avicula barklyi* Moore (1870, p. 245, pl. 11, figs 1-2); see Newton (1915, p. 225) for synonomy.

Diagnosis: Inequivalve, inequilateral, biconvex, or concavo-convex shells, right valve less inflated and smaller than the left valve. Beaks anterior to submedian, left valve with small crenulate anterior ear, both valves with large posterior ear or wing. Ornament of radiating costae in up to four orders, and fine concentric laminae, which may be produced into spines where crossing the costae. Hinge less than maximum length of shell: ligament area external, with opisthocline ligament pit in each valve, anterior part of area raised and ear-like in right valve, with a narrow byssal notch in front.

Hinge plate in left valve with strong anterior tooth that fits under the raised anterior part of the ligament area on the right valve. Muscle scars depressed; posterior scar in each valve large and suboval, median or slightly posterior, linked by pitted pallial line to a deep anterior pit

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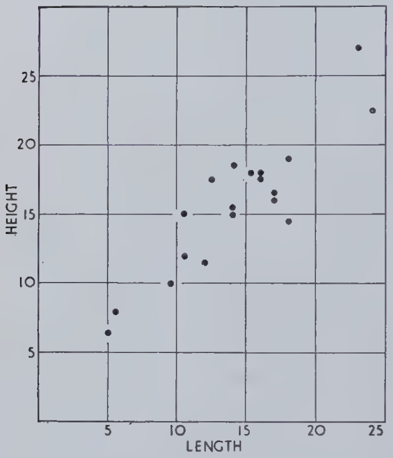


FIG. 1.—Left valves of *M. incurvata*, length plotted against height, showing a rectilinear development with increase in size.

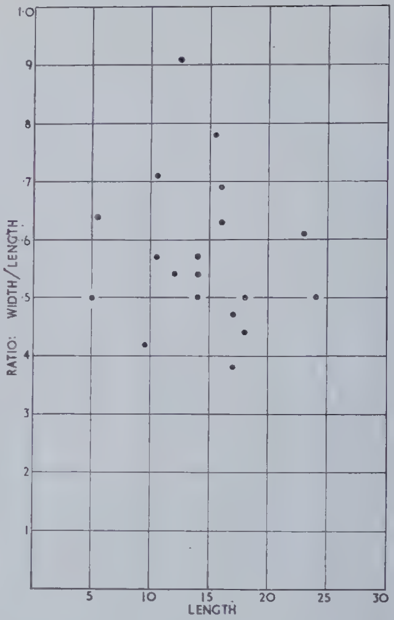


FIG. 2.—Left valves of *M. incurvata*, showing a wide scatter: there is no significant change of ratio of width to length with increase in size.

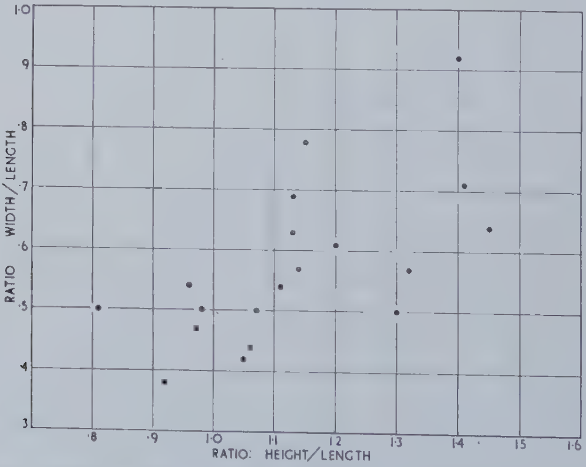


FIG. 3.—Left valves of *M. incurvata*. Ratio of height/length, plotted against the width/length ratio, suggesting that relatively high shells are also relatively inflated, independent of size (cf. Fig. 2).

below the beaks. Possibly Jurassic, chiefly Lower Cretaceous of Australasia.

DISCUSSION. Superficially the hinge in the left valve resembles that of the Permian genus *Eurydesma* Morris (1845), which perhaps lead

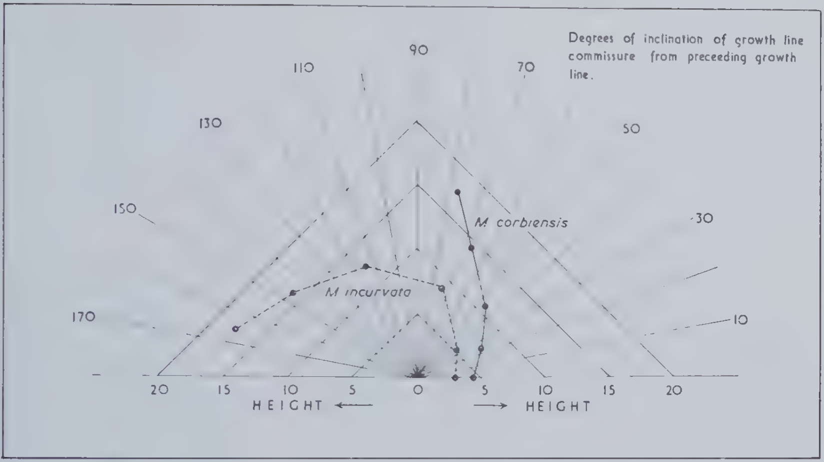


FIG. 4.—Diagram showing that the left valve of *M. incurvata* is more incurved than that of *M. corbiensis* Etheridge. The holotype T.M. 2070 of *M. incurvata* is compared with a left valve of *M. corbiensis* at the New Zealand Geological Survey, WM 7443, from the Barcoo River, South Central Queensland. The height of the two specimens is measured at intervals from strong growth-lines. These heights are plotted against the angle in degrees between that growth-line and the preceeding growth-line, from commissure to commissure, viewed from a posterior aspect. This shows the gradual incurvature of the shell. For simplicity the beak is considered to be in line with the first prominent growth-line.

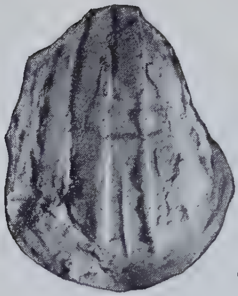
David and Browne (1950) to suggest that *Maccoyella* descended from this genus. However, *Eurydesma* is almost equivalve, lacks a ligament pit as pointed out by Dickins (1957), and has a strong tooth in the right instead of the left valve.

Maccoyella incurvata n.sp. Figs 1-18.

MATERIAL. More than fifty natural casts are available, chiefly internal casts of the left valve. Only five separate right valves are present, and four specimens with valves conjoined, of which one specimen is almost complete. A good range in size is represented, specimens ranging from five to over twenty millimetres in length, and most details are available, except for shell structure. Moulds of an I.C.I. plastic, "Welvic" (polyvinyl chloride in Tritolyl phosphate) were used for preparing positives of the casts.

TYPES. HOLOTYPE: Specimen T.M. 2070 (a well preserved specimen with conjoined valves). Figs 5-7.

PARATYPES: Eighteen left valves, displaying internal features, and complete enough to be measured, three external casts of left valves, three specimens with valves conjoined, and five right valves: T.M. 2065-2069: 2071-2094: New Zealand Geological Survey, Lower Hutt.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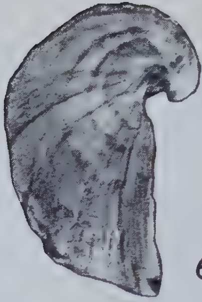
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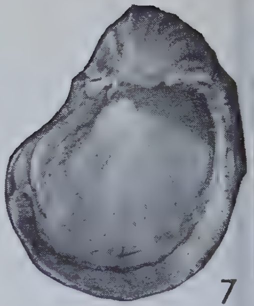
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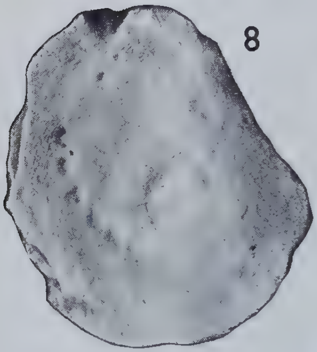
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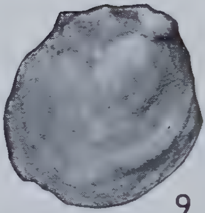
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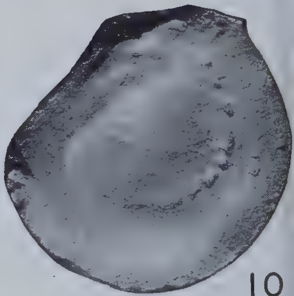
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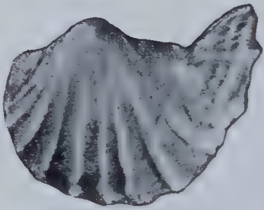
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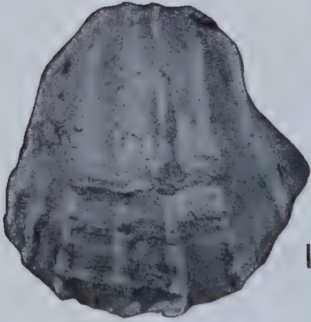
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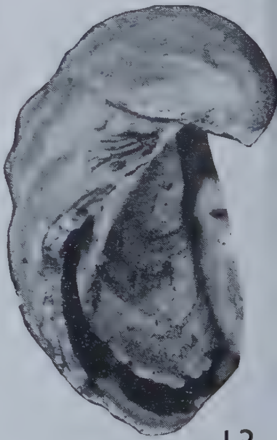
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Maccoyella incurvata n.sp.
(× 2, approximately)

Figs 5, 6, 7,—Holotype T.M. 2070 from left, posterior and right aspects, showing the inflated left valve with highly incurved beak, and almost flat right valve.

Fig. 8.—Mould of internal cast of right valve T.M. 2076, showing muscle scars and pallial line. The notch at the damaged dorsal margin lies under the raised anterior part of the ligament area.

Fig. 9.—Mould of external cast of right valve T.M. 2078, tilted to show the ligament area with the opisthocline ligament pit, and ear-like anterior part.

Fig. 10.—Internal cast of right valve T.M. 2077 showing muscle scars and pallial line. Dorsal margin damaged.

Fig. 11.—Ventral part of external mould of left valve, T.M. 2071, showing ornament.

Fig. 12.—Beak and posterior ear of external mould, T.M. 2080.

Fig. 13.—Mould of T.M. 2066, showing incurved left valve, and small flat right valve.

Unmeasured topotypes have been sent to the Universities of New England, Armidale; Queensland, at Brisbane, and Victoria, at Wellington; the Bureau of Mineral Resources, Canberra, the Australian Museum, Sydney, and the British Museum (Natural History), London.

DIAGNOSIS. Small opisthocline shells of gryphaeoid appearance, the left valve well inflated with a highly incurved beak, right valve almost flat. Hinge short, ligament area highly concave in left valve, inclined ventrally from the hinge towards the right in right valve, anterior area in left valve little depressed. Hinge plate of left valve large, with prominent anterior tooth, and posterior buttress. Muscle scars as in other species. Ornament of eight to ten first and a few second order costae, rare tertiary costae, and spines.

DIMENSIONS. See Table 1, and Figs 1-3.

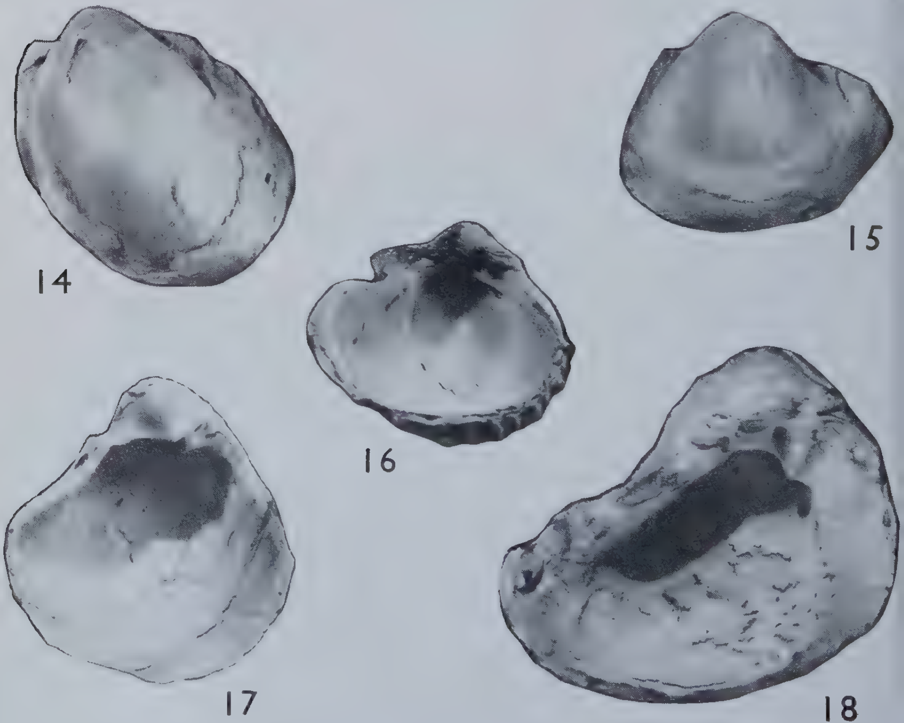
DESCRIPTION. *External.* The shells are opisthocline and relatively small for the genus. The left valve is well inflated, with a strongly incurved beak: the right valve is almost flat, being gently convex near the beak and gently concave anteriorly in the holotype, but entirely convex in some other specimens; it fits into the left valve like an operculum. Shape varies. Some specimens, including the holotype, are relatively high and inflated, with the beak placed comparatively close to the anterior margin. The umbonal angle in these shells is close to 100°. Other shells are more rounded or slightly elongated in outline, and the beak is more centrally situated, with the umbonal angle reaching up to 130°. In high shells such as the holotype the anterior margin is most extended just below mid-length, and the posterior margin is prolonged close to the lower third of the height. The anterior and posterior margins of more elongated specimens are most extended close to mid-height.

The hinge is about half as long as the shell. A tiny anterior ear is developed in the left valve, with strong wrinkles parallel to the anterior margin, and an obtuse cardinal angle, measuring about 100°. The posterior wing extends nearly the length of the hinge. It is convex in the left valve, and concave in the right, and the angle at the posterior cardinal extremity measures close to 140°.

On the left valve the ornament comprises eight to ten strong well spaced primary costae and a few secondary costae, with rare tertiary costae in large specimens. About seven very fine costae occur on the right valve, with no secondary costae. No radial ornament occurs on the ears of either valve. The valves are crossed by numerous fine concentric laminae, about two occurring in every vertical millimetre, with rounded crests and sharply defined interspaces. The laminae arch dorsally between the costae, and prominent laminae are produced into spines where crossing the costae.

The ligament area of the left valve lies approximately normal to the commissure, and is very concave vertically. That of the right valve is plane, and faces the dorsal margin, inclined from the hinge at about 45° from the commissure ventrally towards the right. This unusual attitude enabled the ligament to lie between converging areas as usual. In both valves the area is ornamented with horizontal and faint vertical striations. The median third is occupied by an opisthocline ligament pit in which the horizontal striae are well defined. In the left valve the pit is arch-shaped in outline and is bordered by a low ridge each side in some valves; that of the right valve is more triangular in shape. Usually the ligament area in front of the pit in the left valve is gently concave, and bounded anteriorly by a ridge. The anterior part of the area in the right valve is raised into a cuneiform ear-like projection with a small byssal notch in front.

Internal: In the left valve is a large hinge plate, with a strong triangular tooth close to the anterior margin. A weak ridge lies on the



Maccoyella incurvata n.sp.
(× 2, approximately)
FIG. 14.—Internal cast of relatively high left valve T.M. 2087.
FIG. 15.—Internal cast of relatively elongated left valve T.M. 2092.
FIG. 16.—Mould of internal cast of left valve T.M. 2084, tilted to show the ligament area and the anterior tooth.
FIG. 17.—Mould of internal cast of left valve T.M. 2079.
FIG. 18.—Mould of internal cast of left valve T.M. 2065, showing ligament pit and anterior tooth.

TABLE 1.—Dimensions (in millimetres).

Specimen (T.M.)	Length (L)	Height (H)	Width (W)	Hinge Length	Umbonal Angle	Angle of maximum inflation from vertical	Distance of beak from anterior margin (L)
LEFT VALVE							
2090	5	6·5	2·5	3·3	130	15	0·50
2091	5·5	8	3·5	3		10	0·45
2068	?9·5	10	4	5·5	105	7	0·32
2082	10·5	12	6	4·5	100	18	0·52
2069	10·5	15	7·5	?6	120	10	0·47
2074	12	11·5	6·5		100	25	0·42
2067	12·5	17·5	11·5	7·5	90	20	0·40
2083	14	?15	7	9		22	0·36
2088	14	15·5	7·5	6	110	30	0·32
2095	14	18·5	8	6	100	22	0·32
2070	15·3	18	12	8·5	110	28	0·40
2073	16	18	11	7·5		15	0·44
2087	16	18	10	7·5	110	35	0·38
2081	17	16	6·5	8·5	125	15	0·41
2084	17	16·5	?8		100	20	0·44
2092	18	14·5	9	?7	130	10	0·39
2079	18	19	8	+8	130	15	0·36
2072	23	27	14	?8	90	35	0·35
2065	24	22·5	12	9	100	35	0·27
RIGHT VALVE							
2094	9·5	9·5	?1	6			
2070	12	11·5					
2078	14	12·5	1·8	6		18	
2093	14	13	1·8	?6		20	
2077	18·5	17	?2	9		25	
2076	20	23	2·5	8			

plate below the anterior margin of the ligament pit of some shells, continuing from the ridge that may bound the anterior margin of the ligament pit. Posteriorly, the ventral margin of the hinge plate is produced into a strong buttress. The tooth fits into a socket under the ear-like anterior part of the ligament area in the right valve, and a weak depression near the posterior dorsal margin receives the buttress of the left valve.

In each valve the posterior muscle scar lies just behind the beak, close to mid-height. It is large, oval or subrectangular in shape, and deeply impressed. The anterior scar is a tiny pit situated close to the dorsal margin, a little in front of the beak. The two scars are joined by a short pitted pallial line.

GROWTH CHANGES. Small specimens about five millimetres long are well inflated, and somewhat rounded in outline. As the shell increases in size, the left valve becomes more and more incurved (Fig. 4), and the shape more opisthocline, but no significant change occurs in the height/length ratio.

RESEMBLANCES. *M. incurvata* is distinguished by its considerable degree of gryphaeation. It is apparently close to an Aptian species from Australia, *M. corbiensis* (Moore, 1870, p. 246, pl. 11, fig. 7; Etheridge sr, 1872, pl. 19, fig. 3; Tenison-Woods, 1883, pl. 12, fig. 6?; Etheridge jr, 1892, pp. 458, 563, pl. 22, figs 8, 9; 1902a, p. 21, pl. 1, figs 6-10; 1902b, p. 13, pl. 1, figs 9, 10; 1907, p. 320, pl. 61, figs 1-6). Like the new species, *M. corbiensis* is a relatively small shell, mature specimens being generally only one and a half to twice as large as the largest New Zealand specimens, and the left valve is comparatively inflated, with a moderately incurved beak. However, the Australian species is usually less inflated than *M. incurvata,* the ratio of width to length measuring from 0·3 to 0·4 in specimens of *M. corbiensis* at the New Zealand Geological Survey from Maryborough, Woody Island, and Barcoo River, Queensland, whereas the width/length ratio of *M. incurvata* is generally between 0·5 and 0·7. Moreover, the beak of *M. corbiensis* is considerably less incurved than *M. incurvata* (Fig. 4). Also, the costae are more numerous on the Australian shells, and appear to be lower. The area on the left valve of *M. corbiensis* is less concave vertically and less inclined to the commissure than in *M. incurvata,* and the area of the right valve is almost normal to the commissure, as is to be expected in a less inflated shell. Like *M. incurvata,* the Australian species has a high umbonal shelf in the left valve, with a strong anterior tooth, and low posterior buttress, although these features are not as strongly developed as in the new species.

These two species stand apart from other well known *Maccoyella,* such as *M. barklyi* (Moore) and *M. reflecta* (Moore). The latter two species are larger, less inflated shells with beaks that are little incurved, and with larger ears, and a deep byssal notch in the right valve. The hinge plate of *M. reflecta* and *M. barklyi* is small, the anterior tooth short and massive, and the posterior buttress of the left valve rarely present, being visible in only one figured specimen of *M. barklyi* (Etheridge, 1902a, pl. 3, fig. 5).

In ornament *M. incurvata* resembles the left valve figured as "*Oxytoma*" *rockwoodensis* Etheridge (1892, pl. 24, fig. 15). The Australian shell is less inflated, with a larger posterior wing than in the new species. Its internal details are undescribed. In 1907 Etheridge suggested that *rockwoodensis* is possibly identical with a variety of *M. corbiensis,* but David and Browne (1950) referred to the species as distinct.

Specimens of the possible Jurassic species reported from Western Australia by Brunnschweiler (1953) have been kindly loaned by Mr Cannon from the Bureau of Mineral Resources, Canberra. The specimens are internal and external casts, chiefly of the left valve, and none show details of the hinge, so that their generic position is uncertain. Compared with the New Zealand shells, the Australian specimens are much wider, larger, and less inflated, with a wider, less incurved umbo, and a less defined posterior wing. Costae are more numerous.

AGE: *Maccoyella* is represented in the Upper Jurassic by one possible species from Oxfordian to Lower Tithonian beds of Western Australia (McWhae *et al.*, 1958, p. 88), and in the Lower Cretaceous by several Aptian and one Albian species (David and Browne, 1950). *M. incurvata* presumably falls within this range, and as some doubt is attached to the Jurassic occurrence of *Maccoyella*, is more likely to be Lower Cretaceous than Jurassic.

This age is supported by further evidence. A specimen of *Pleuromya* Agassiz that occurs with *M. incurvata* at GS 6292 has ornament like that of an undescribed *Pleuromya* from the Aptian Taitai beds at GS 3154, Koranga, although the two differ in shape. The concentric wrinkles of these two are stronger and more regularly disposed than in the two Jurassic species of *Pleuromya* from New Zealand, *P. milleformis* Marwick (1953) and *P. urnula* Marwick (1953).

In the nearby Waimana Valley, Mr G. W. Grindley has found an *Inoceramus* at GS 6294, in beds correlated on lithology with the beds at Kaihikatea. The *Inoceramus* somewhat resembles the Neocomian and lower Aptian species *I. neocomiensis* d'Orbigny, figured in Woods (1911, pl. 45, figs 1, 2). The beak of the European shell is wider and more prominent, and the angle between the hinge and maximum inflation of the shell is greater, but the two are crudely similar in general appearance and ornament.

Thus, on the evidence of *Pleuromya* and *Inoceramus, M. incurvata* is more likely to be Lower Cretaceous than Jurassic.

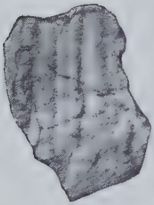
After mapping the area, Mr Grindley (pers. comm.) also considers that the species is possibly Lower Cretaceous, because no major break was found between the beds with *M. incurvata*, and overlying Mokoiwi (?Lower Aptian) beds.

Maccoyella magnata Marwick Figs 19-21.

1939 *Maccoyella magnata* Marwick: 462, pl. 61, figs 1, 2.

DISCUSSION: The only known specimen is a large left valve, specimen T.M. 2121 from GS 1989, Raukumara Peninsula. Marwick (1939) compared it to *M. reflecta* (Moore) from the Aptian of Australia.

Indeed there seems to be little to distinguish *M. magnata* from the Australian species. Marwick (1939, p. 436) stated that the umbonal angle of the New Zealand left valve is only 120°, compared with an angle of 180° in left valves of *M. reflecta*, but, judging from the specimens of *M. reflecta* figured by Tenison-Woods (1883, pl. 12, fig. 4), Etheridge (1892, pl. 23, fig. 1), and Etheridge (1902a, pl. 1, fig. 3; pl. 2, fig. 1), the umbonal angle of the left valve in *M. reflecta* varies between only 110° and 130°. Unlike *M. reflecta*, Marwick pointed out, the New Zealand specimen seems to have no posterior wing. However, the posterior dorsal margin of the New Zealand specimen is broken, so that it is difficult to be sure if a wing was not once present.



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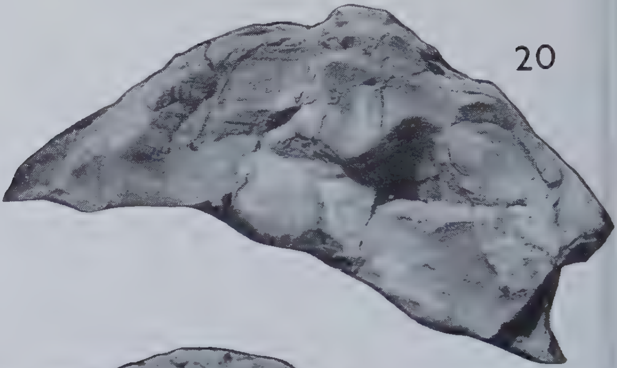

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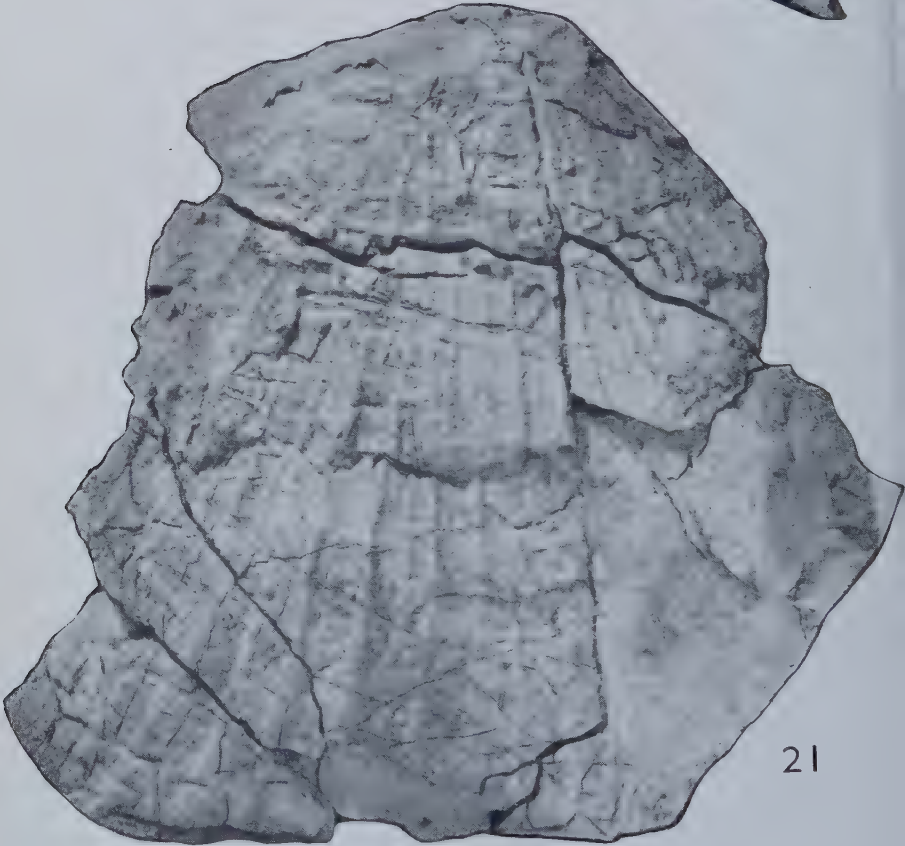

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Maccoyella magnata Marwick (Holotype)
(× 1, approximately)

FIG. 19.—External cast, showing the radial costae crossed by close-set concentric laminae. T.M. 2121.

FIG. 20.—Internal view of the hinge region of the left valve, showing the damaged anterior ear and beak, with the posterior dorsal margin broken. Below and in front of the wide ligament pit is a massive tooth, on a short hinge plate.

FIG. 21.—Exterior of left valve.

Certainly the wing must have been small, but possibly it was little smaller than in some specimens of *M. reflecta* figured by Etheridge (1892, pl. 23, fig 1; 1902a, pl. 1, fig. 3).

The two species are similar in shape, size, and ornament as noted by Marwick, although the costae in *M. magnata* are spaced a little more widely than in some specimens of *M. reflecta*. The number of costae in 25 millimetres measured concentrically across the shell at 55 millimetres below the beak is ten to eleven in *M. magnata*, compared with twelve in the specimen of *M. reflecta* figured by Etheridge (1902a, pl. 2, fig. 1) and in a specimen at the New Zealand Geological Survey, W.M. 998, from Woody Island, Harvey Bay, Queensland. There are only nine costae at a similar position in another specimen figured by Etheridge (1892, pl. 23, fig. 1), so that the number of costate in *M. magnata* appears to be within the range of variation for *M. reflecta*. By leaching the shell with acid from a fragment of the external cast of *M. magnata*, it is seen that fine concentric laminae are also present (Fig. 19), two to three occurring in one millimetre (measured vertically). These concentric laminae are true external ornament and not due to weathering as Marwick claimed.

The posterior ligament area and anterior ear of the New Zealand specimen are damaged (Fig. 20). Otherwise the ligament area resembles that of *M. reflecta* figured by Etheridge (1920a, pl. 3, fig. 3) from Mt. Poole, except that the anterior part is less concave in the Australian shell. However, other specimens of *M. reflecta* figured by Etheridge (1902a, pl. 1, fig. 4; pl. 2, fig. 2) from the Mount Stuart Run have a deeply concave anterior area, like that of *M. magnata*. To the writer it appears that *M. magnata* is probably identical with *M. reflecta*, but as the right valve and posterior margin of the left valve are unknown, there can be no certainty; nor, for the same reasons, is it sure that *M. magnata* is a separate species.

AGE: The possible identity of *M. magnata* with *M. reflecta* strengthens the Aptian age suggested by Marwick for the New Zealand shell. Because *M. magnata* has quaternary costae, Marwick considered that the specimen might indicate an upper Aptian age, based on analogy with *M. corbiensis* and *M. barklyi*, which develop quaternary costae high in the Aptian, according to Whitehouse (1926). But all species may not have displayed a similar change in ornament, nor need the change have been synchronous, so that this refined correlation is not yet confirmed.

ACKNOWLEDGEMENTS

The writer is grateful to Dr L. R. Cox, British Museum (Natural History), London, for his comments on the new species. Dr H. W. Wellman, Victoria University of Wellington, and Mr G. W. Grindley, New Zealand Geological Survey, discussed the stratigraphic position of the Kahikatea *Maccoyella*. A series of Australian *Maccoyella* species

were kindly given to the New Zealand Geological Survey by Mr H. E. Evans and specimens of *M. corbiensis* were kindly given by Dr J. W. Evans, Australian Museum. Specimens of *M. barklyi* var. *mariaeburiensis* Etheridge (1892, p. 563, pl. 22, fig. 3; pl. 42, figs 4, 5) were loaned from the University of Queensland by the Curator of the Museum, Mr Colliver, and specimens of the undescribed Jurassic ?*Maccoyella* were loaned from the Bureau of Mineral Resources, Canberra, by Mr Cannon. Photographs are by Mr S. N. Beatus, New Zealand Geological Survey.

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STRATIGRAPHY OF THE LOWER WAIPARA GORGE, NORTH CANTERBURY*

By D. R. GREGG, New Zealand Geological Survey, Department of Scientific and Industrial Research, Christchurch

(Received for publication, 23 January 1959)

Summary

In the lower Waipara Gorge, North Canterbury, sediments ranging in age from Awamoan to Holocene form a sequence about 4000 ft thick. There is an unconformity below the Waitotaran, and no Taranaki Series is present. Marine sedimentation gave way to non-marine about the beginning of the Nukumaruan. Two new formations are established; the Double Corner Shell-beds of Waiauan age, and the Greenwood Formation of Waitotaran to possibly Nukumaruan age. The marine sediments contain rich molluscan faunas.

INTRODUCTION

The lower Waipara Gorge lies near the northern end of the Canterbury Plains where the Waipara River has cut through a low range of hills adjacent to the coast (Fig. 1). The gorge is 35 miles from Christchurch, and is the nearest, as well as the most accessible, richly fossiliferous locality. It falls within N.Z.M.S.1 sheet S 68. Grid references are given in terms of the provisional datum as shown on the 2nd edition (1949) of N.Z.M.S.1 S 68 and 69.

PREVIOUS GEOLOGICAL WORK

As early as 1849 C. Forbes (1855, p. 525), assistant surgeon on the Admiralty survey ship H.M.S. *Acheron*, visited the gorge and recorded the presence of "a calcareous and sometimes sandy shell rock, and . . . a tertiary blue clay with shells."

In February 1850, Torlesse found a seam of coal in the south bank of the Waipara near the mouth of the river (in Maling, 1958, p. 130).

Hector (1878, p. 202, 208) in 1867 collected 283 fossils from the lower gorge of the Waipara. In an account of the Waipara district (1869, p. xii) he described the rocks of the gorge as being "faulted and tilted at a high angle, although deposited round hills of the older tertiary strata, the beds comprising which appear to have remained almost horizontal." In his "Catalogue of the Colonial Museum" (1870, p. 179) Hector listed 22 molluscan fossils from the lower Waipara Gorge. The fossils were listed mainly by generic names only, but the name *Lutraria solida* was published for the first time (without description).

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*This paper is based on part of a thesis submitted to the University of Canterbury in 1950.

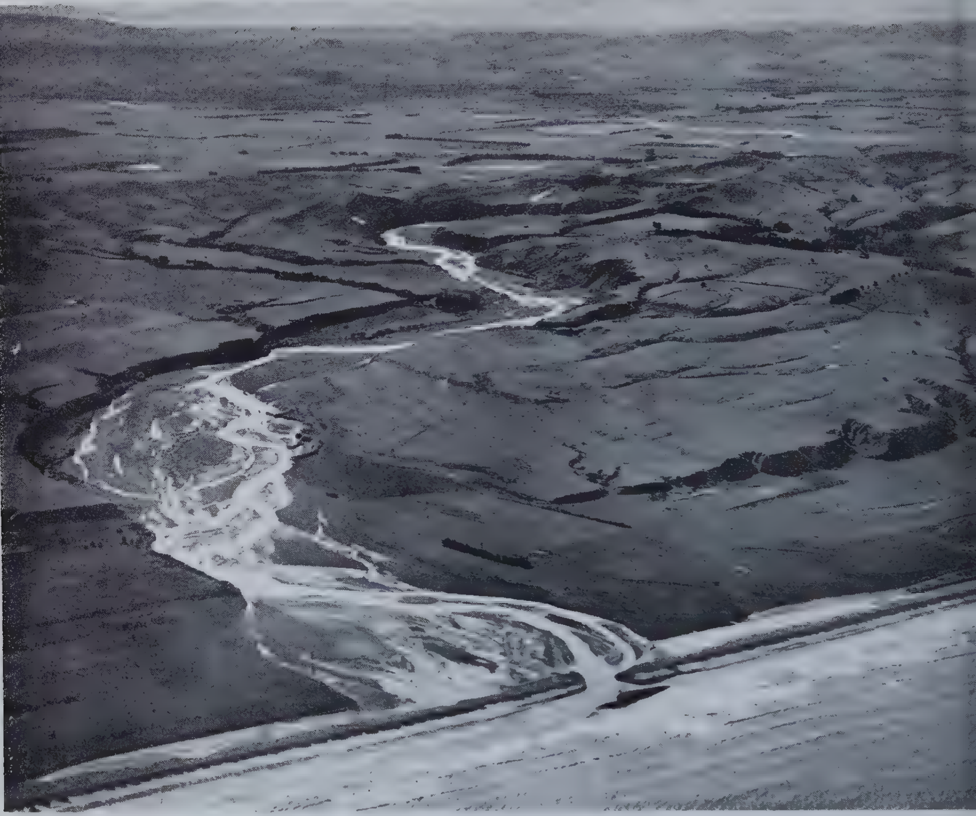

FIG. 1.—Lower Waipara Gorge from near the mouth of the Waipara looking north-west. The river leaves its middle gorge in the left background, runs east just below the level of the Canterbury Plains, and then turns south cutting between the Amberley Hills and the Mount Cass Range to form its lower gorge. The Teviotdale Terrace is truncated by an old sea-cliff in the right foreground, and in front of the cliff is the Holocene Amberley strand-plain. —*Photo*: *V. C. Browne.*

Hutton (1873, p. 19, 21, 33) described three new molluscan species from the lower Waipara Gorge, *Lutraria solida, Cytherea enysi* (= *Eumarcia* (*Atamarcia*) *enysi*, see Marwick, 1927, p. 629), and *Lima crassa* (name dismissed by Finlay, 1930, p. 37-8). Hutton later (1877, p. 52) listed 16 species collected principally by Haast and Buchanan.

McKay (1877, p. 50, 53) correlated the fossiliferous beds of the lower Waipara Gorge with the shell beds of the Grey River, and mentioned the gravels making up the Amberley Hills.

Haast (1879, p. 316-23) placed the rocks of the lower Waipara Gorge in his Pareora Formation. He recorded the finding of several

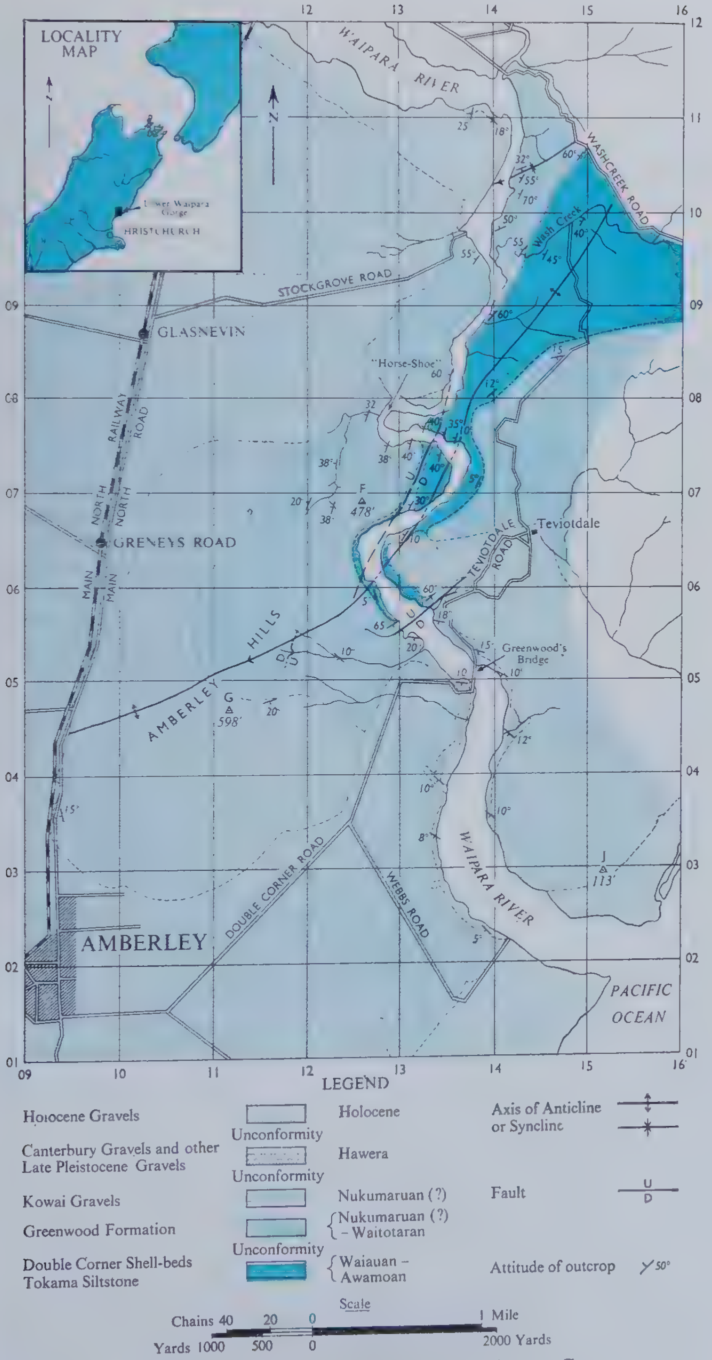

FIG. 2.—Geological map of lower Waipara Gorge.

vertebrae and portions of a lower jaw of whales, and the presence of lignite at the mouth of the Waipara.

Hutton (1888, p. 262-3) in a paper on the railway cuttings in the Weka Pass proposed the term Greta beds, for strata which appeared to be younger than the beds of the lower Waipara. He believed the silt and gravels succeeding the Greta beds (i.e. the Kowhai Series of Thomson, 1920) to be of the same age as the gravels of the Amberley Hills.

The most detailed account of the geology of the lower Waipara Gorge was published by Speight (1912), who described the structure and stratigraphy and gave lists of fossils collected by Marshall and Speight and identified by Suter. Speight later (1914) listed fossils collected from strata cropping out downstream from Greenwood's bridge.

Thomson and Cotton visited the lower Waipara in 1911 (Speight, 1912, p. 231), and Thomson (1912, p. 9) questioned the value of Speight's correlations. Thomson, in 1913, collected fossils from the strata near Greenwood's bridge, and also from beds he termed the "Grey Marls" (Suter, 1921, p. 45).

Suter (1913) described three new species of Mollusca from the lower Waipara Gorge collected by Marshall and Speight; *Clavatula neozelanica* (= *Austrotoma neozelanica*, see Powell, 1942, p. 75), *Terebra orycta* (= *Zeacuminia orycta*, see Finlay, 1930, p. 47), and *Chione speighti* (= *Bassina speighti*, see Marwick, 1927, p. 619). Suter (1914, p. 39) described *Modiolus huttoni* from the lower Waipara. In a later paper (1917, p. 4) he described *Calliostoma waiparaense* (= *Maurea waiparaensis*, see Finlay, 1927, p. 371; Marwick, 1928, p. 476). A list of fossils collected by Thomson in 1913 was given by Suter (1921, p. 45).

Marshall (1919, p. 250) placed the "sandy beds of the Lower Waipara Gorge" in his Target Gully Series. Morgan (1919, p. 219) wrongly correlated the "layers of calcareous conglomerate" at the base of the Greenwood Formation with the Mount Brown limestones.

Speight (1919, p. 278-9) described the section exposed on the right bank near the mouth of the Waipara, and correlated the sands, gravels, and lignite with his Kowai Series, a name he proposed in the same paper.

Marwick (1924, p. 560-1) described the variations of *Polinices intracrassus* from the lower Waipara Gorge. Withers (1924) recorded four cirripedes from the lower Waipara. The holotype of *Balanus tubulatus* and paratypes of *Balanus amphitrite* var. *acutus* were collected by Thomson in 1913. Finlay (1926) described two new species of gastropod viz. *Austrotoma obsoleta* and *Zelandiella fatua*.

Speight and Jobberns (1929, p. 226-7) compared the section exposed at the "Horse-shoe" with that in Wash Creek, and postulated an unconformity to explain the absence of the Waiauan shell-beds in Wash Creek.

Jobberns (1937) described the geomorphology of the lower Waipar Gorge. He named various surfaces including the Teviotdale Terrace.

Mason (1941) correlated the molluscan shell-bed at the top of his Tokama Series with shell-beds in the lower Waipara Gorge.

Wilson (1955) proposed the terms Canterbury Gravels and Canterbury Surface and mapped their extent in North Canterbury.

STRATIGRAPHY

The main features of the stratigraphical succession are given in the composite column (Fig. 3).

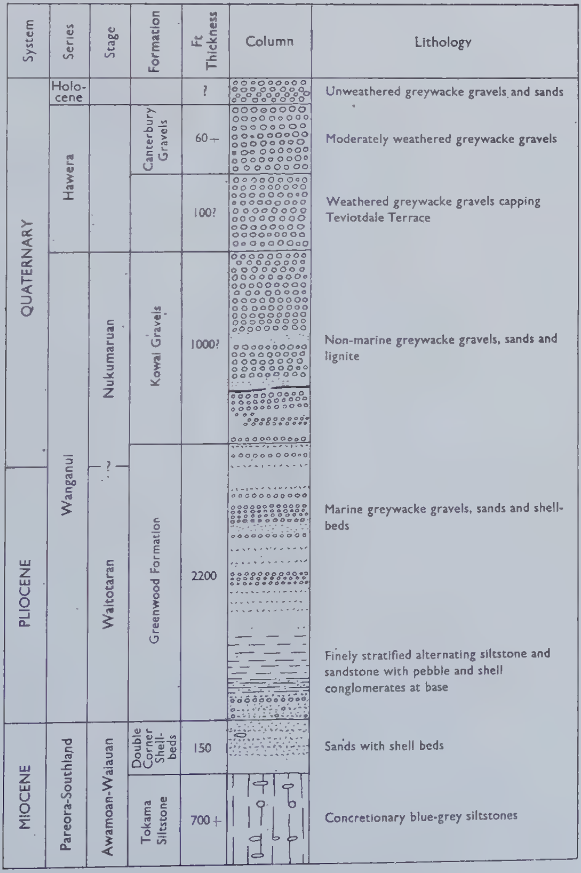
System
Series
Stage
Formation
Ft Thickness
Column
Lithology
Holocene
?
Unweathered greywacke gravels and sands
Canterbury Gravels
60+
Moderately weathered greywacke gravels
Hawera
100?
Weathered greywacke gravels capping Teviotdale Terrace
QUATERNARY
Nukumaruan
Kowai Gravels
1000?
Non-marine greywacke gravels, sands and lignite
Wanganui
?
PLIOCENE
Waitotaran
Greenwood Formation
2200
Marine greywacke gravels, sands and shell-beds
Finely stratified alternating siltstone and sandstone with pebble and shell conglomerates at base
MIOCENE
Pareora-Southland
Awamoan-Waiauan
Double Corner Shell-beds
150
Sands with shell beds
Tokama Siltstone
700+
Concretionary blue-grey siltstones

FIG. 3.—Composite stratigraphic column.

Tokama Siltstone

NAME

The name Tokama Series was proposed by Mason (1941, p. 120) for several hundred feet of blue-grey sandy mudstone and siltstone, overlying his Whiterock Limestone and best exposed in the east and west branches of the Grey River. Mason included at the top of the Tokama Series, his *Polinices* shell-bed. This is of Waiauan age and can be correlated with the Double Corner Shell-beds of the lower Waipara Gorge. The major part of the Tokama Series which lies beneath the Polinices shell-bed is renamed the Tokama Siltstone.

DISTRIBUTION AND CONTENT

The Tokama Siltstone is the oldest formation exposed in the lower Waipara Gorge. It is exposed along the main anticlinal axis, and

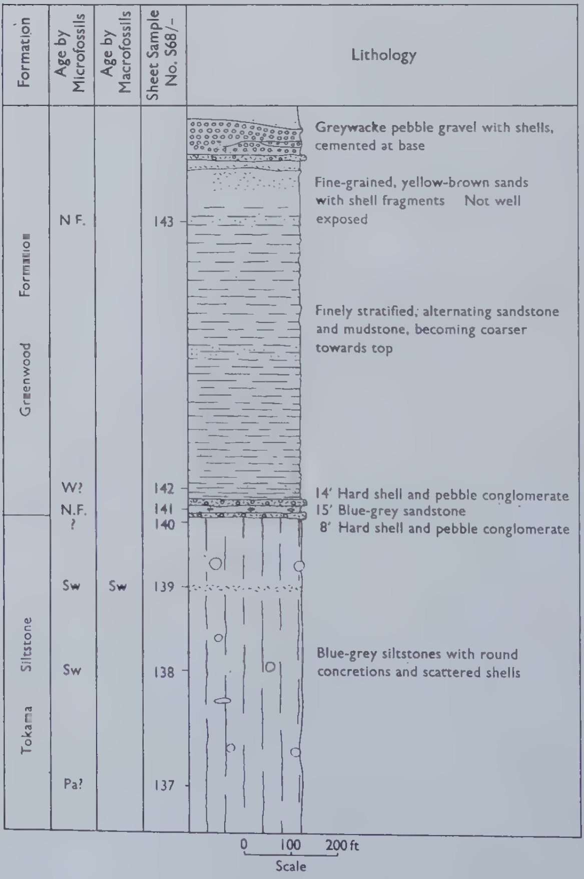
Formation
Age by Microfossils
Age by Macrofossils
Sheet Sample No. S68/-
Lithology
Greenwood Formation
Tokama Siltstone
N F.
W?
N.F.
?
Sw
Sw
Pa?
Sw
143
142
141
140
139
138
137
Greywacke pebble gravel with shells, cemented at base
Fine-grained, yellow-brown sands with shell fragments Not well exposed
Finely stratified; alternating sandstone and mudstone, becoming coarser towards top
14′ Hard shell and pebble conglomerate
15′ Blue-grey sandstone
8′ Hard shell and pebble conglomerate
Blue-grey siltstones with round concretions and scattered shells
0
100
200 ft
Scale

FIG. 4.—Wash Creek stratigraphic column.

extends from Washcreek Road in the north-east to the Amberley Hills in the south-west. The anticline plunges to the south-west and the oldest rocks crop out near the north-east end of the axis. In Wash Creek (Fig. 4) about 700 ft of blue-grey concretionary siltstones make up the Tokama Siltstone. They are comparatively soft, except where cemented into calcareous concretions, and contain scattered shells. In the "Horse-shoe" the lowest 60 ft of beds exposed belong to the Tokama Siltstone (Fig. 5). They are again blue-grey concretionary siltstones with scattered shell fragments.

RELATION TO UNDERLYING ROCKS

The base of the Tokama Siltstone is not exposed in the area dealt with in this paper, but farther to the north-east it probably rests conformably on the Grey Marls of Otaian age.

PALEONTOLOGY

MACROFOSSILS:—The Tokama Siltstone in Wash Creek contains Mollusca and a few Brachiopoda scattered throughout. The Brachiopoda, which are poorly preserved, were referred by Dr R. S. Allan to the genus *Neothyris*. The coral *Flabellum* occurs in many places throughout the section. A shell-bed crops out 150 ft below the top of the formation. The locality is marked by the presence of a water-fall 20 ft high. The Mollusca are well preserved and easily collected. Dr C. A. Fleming identified the following species.

S 68/139 GS 4924

Cucullaea n.sp. aff. *australis* (Hutt.)
Limopsis lawsi King
Lentipecten hochstetteri (Zitt.)
Lima aff. *colorata* Hutt.
Spissatella cf. *trailli* (Hutt.)
Atrina cf. *lata* (Hutt.)
Pleuromeris aff. *zelandica* (Desh.)
Zeacolpus n.sp. aff. *pukeuriensis* Marw.
Struthiolaria (*Callusaria*) aff. *callosa* Marw.
Proxiuber sp.
Austrofusus (*Nassicola*) *speighti* Marw.
A. (*Neocola*) sp.
A. (*Zelandiella*) n.sp. aff. *subnodosus* (Hutt.)
Mauithoe insignis (Marw.)
Metamelon sp.
Comitas aff. *fusiformis* (Hutt.)
Scrinium aff. *strongi* Marw.
Dentalium (*Fissidentalium*) cf. *solidum* Hutt.
Flabellum sp.

Age: Waiauan.

No macrofossils were collected from the Tokama Siltstone at the "Horse-shoe", but scattered shell fragments and *Flabellum* are present.

MICROFOSSILS:—Four samples from the Tokama Siltstone in Wash Creek yielded Foraminifera.

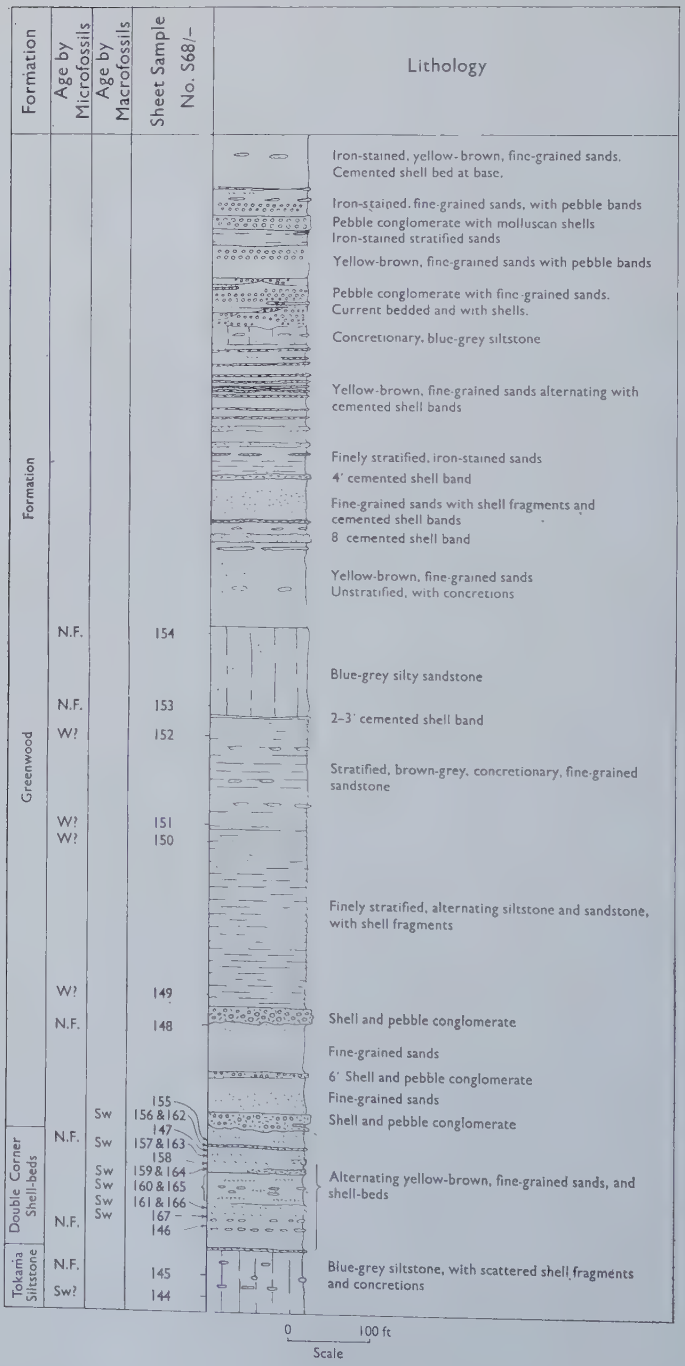
Formation
Age by Microfossils
Age by Macrofossils
Sheet Sample No. S68/–
Lithology
Greenwood Formation
Double Corner Shell-beds
Tokama Siltstone
Iron-stained, yellow-brown, fine-grained sands. Cemented shell bed at base.
Iron-stained, fine-grained sands, with pebble bands
Pebble conglomerate with molluscan shells
Iron-stained stratified sands
Yellow-brown, fine-grained sands with pebble bands
Pebble conglomerate with fine-grained sands. Current bedded and with shells.
Concretionary, blue-grey siltstone
Yellow-brown, fine-grained sands alternating with cemented shell bands
Finely stratified, iron-stained sands
4' cemented shell band
Fine-grained sands with shell fragments and cemented shell bands
8' cemented shell band
Yellow-brown, fine-grained sands Unstratified, with concretions
N.F. 154
Blue-grey silty sandstone
N.F. 153
2–3' cemented shell band
W? 152
Stratified, brown-grey, concretionary, fine-grained sandstone
W? 151
W? 150
Finely stratified, alternating siltstone and sandstone, with shell fragments
W? 149
N.F. 148
Shell and pebble conglomerate
Fine-grained sands
6' Shell and pebble conglomerate
155
Fine-grained sands
Sw 156 & 162
Shell and pebble conglomerate
147
N.F. Sw 157 & 163
158
Sw 159 & 164
Sw 160 & 165
Alternating yellow-brown, fine-grained sands, and shell-beds
Sw 161 & 166
N.F. Sw 167
146
N.F. 145
Blue-grey siltstone, with scattered shell fragments and concretions
Sw? 144
0
100 ft
Scale

Fig. 5.—"Horse-shoe" stratigraphic column.

S 68/137 from 600 ft below the top of the Tokama Siltstone contained a fauna, including *Globorotalia miozea* Finlay, which is either lower Southland or Awamoan, and is certainly not older than Awamoan. S 68/138 from 330 ft below the top of the formation had a distinctly different and younger fauna, which with *Cibicides deliquatus* Finlay and *Karreriella cylindrica* Finlay is probably Waiauan. S 68/139 from 150 ft below the top of the formation gave a Waiauan fauna. S 68/140 from 12 ft below the top of the formation was too poor for species to be determined.

From the "Horse-shoe" section one sample yielded Foraminifera. S 68/144 from 60 ft below the top of the Tokama Siltstone had a poor fauna including *Anomalinoides* aff. *spherica* (Finlay) and is probably Waiauan.

AGE AND CORRELATION

On the basis of the molluscan and foraminiferal evidence the Tokama Siltstone covers a considerable time interval from Awamoan near the base to Waiauan at the top. It can be correlated with the type Tokama Siltstone in the Mount Grey District (Mason, 1941) with which it is lithologically similar, with the Mount Brown Beds of the Middle Waipara and Weka Pass (Thomson ,1920, p. 356-63), and with bed M 7 of the Mandamus-Pahau district (Mason, 1949, p. 420-22).

CONDITIONS OF DEPOSITION

The molluscan fauna collected from Wash Creek (S 68/139) differs markedly from the faunas collected from the overlying Double Corner Shell-beds. The shells of the former locality are well preserved and are not at all worn. Many of the pelecypods have both valves still in contact and the whole fauna is evidently biocoenotic; *Cucullaea*, *Atrina*, and *Limopsis* were found with closed valves. The fauna and lithology suggest deposition as off-shore silts. No pebbles of greywacke were found in the siltstones.

Double Corner Shell-beds

NAME

In early reports (Forbes, 1855, p. 525) the district near the mouth of the Waipara River is referred to as Double Corner. This name was adopted for the sheep-station which during the latter part of last century covered most of the country between the Waipara and Kowai rivers. The name Double Corner Shell-beds is here proposed for the brown, fine-grained sands with shell-beds exposed at the "Horse-shoe", and which overlie the Tokama Siltstone.

DISTRIBUTION AND CONTENT

The Double Corner Shell-beds crop out along the banks of the Waipara River near the "Horse-shoe", where they comprise 150 ft of

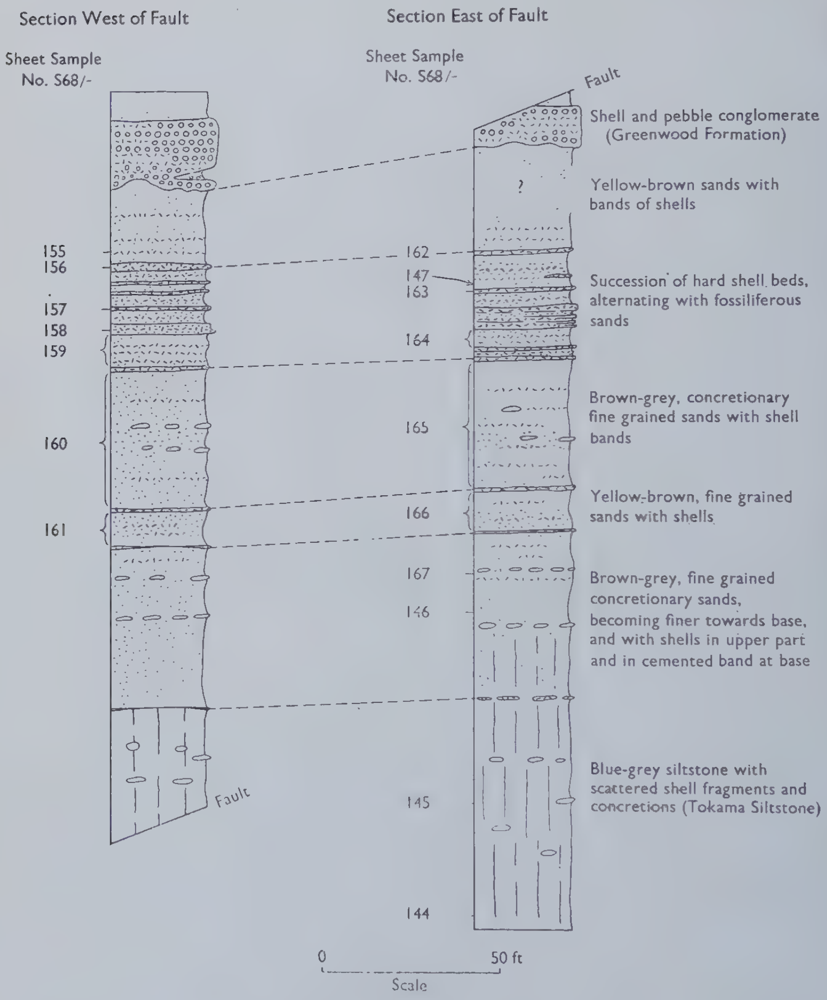
Section West of Fault
Section East of Fault
Sheet Sample No. S68/-
Sheet Sample No. S68/-
Fault
Shell and pebble conglomerate (Greenwood Formation)
?
Yellow-brown sands with bands of shells
155
156
157
158
159
162
147
163
164
Succession of hard shell beds, alternating with fossiliferous sands
160
165
Brown-grey, concretionary fine grained sands with shell bands
161
166
Yellow-brown, fine grained sands with shells
167
146
Brown-grey, fine grained concretionary sands, becoming finer towards base, and with shells in upper part and in cemented band at base
Fault
145
Blue-grey siltstone with scattered shell fragments and concretions (Tokama Siltstone)
144
0
50 ft
Scale

FIG. 6.—Detailed stratigraphic columns of Double Corner Shell-beds on left bank of Waipara River at "Horse-shoe".

brown, fine-grained sands with shell-beds containing abundant Mollusca (Figs 5 and 6). They are not present in Wash Creek, where the Greenwood Formation rests on the Tokama Siltstone.

RELATION TO UNDERLYING ROCKS

The Double Corner Shell-beds conformably overlie the Tokama Siltstone.

PALEONTOLOGY

MACROFOSSILS:—The Mollusca of the beds of the "Horse-shoe" section have been collected many times by geologists, and the species collected by the writer form by no means a complete list. However, all the common species are listed. The fossils are abundant and are easily collected. The beds are repeated by a fault, of about 200 ft throw. The writer made collections from both sides of the fault before he recognized the repetition of the beds. The fossils determined are listed in Table 1. A cetacean vertebra was collected from this formation by the writer in 1946. It came from fossiliferous sands on the left bank of the river at about S 68/138072.

On the basis of the Mollusca Dr Fleming assigns the faunas to the Waiauan.

MICROFOSSILS:—No samples from this formation yielded Foraminifera.

AGE AND CORRELATION

The Double Corner Shell-beds are Waiauan in age on the evidence of Mollusca, and can be correlated with the Mount Brown E limestone and *Hinnites* shell-bed of Weka Pass (Thomson, 1920, p. 362-3), with the *Polinices* shell-bed of the Grey River (Mason, 1941, p. 120-21), and with bed M 8 of the Mandamus-Pahau district (Mason, 1949, p. 422-3).

CONDITIONS OF DEPOSITION

The molluscan faunas of the Double Corner Shell-beds, although rich in individuals, do not cover a wide range of species. The common fossils are *Glycymeris, Polinices, Baryspira, Maoricrypta, Zelandiella, Austrotoma, Turia, Arachnoides, Dentalium, Balanus, Dosinia,* and *Eumarcia.* The faunal content of the successive beds does not vary greatly. The presence of bivalves with both valves still in contact shows that some at least are biocoenotic; *Glycymeris, Turia, Dosinia,* and *Tegulorhynchia* were found with closed valves. These shells which seem definitely biocoenotic were confined to the sandy beds, and did not occur in the concretionary beds and shell conglomerates. These latter beds appear to have derived their shells from sandy areas which supported an assemblage dominated by *Glycymeris, Eumarcia, Dosinia,* and *Turia,* with *Zelandiella, Polinices, Baryspira,* and *Austrotoma* as epifaunal carnivorous members. Many of the pelecypods collected had holes through the shells, which were probably bored by *Polinices*; nearly half the shells of *Turia* contained perforations. *Balanus* was present on some shells of *Polinices* and *Zelandiella.* The echinoid *Arachnoides* was comparatively common, but was always found in a broken state. The modern *Arachnoides* association is found in sands at depths of 4 to 17 fathoms and almost always occurs within the shelter of a harbour mouth or estuary (Powell, 1937, p. 388: 1940, p. 610; Laws, 1950, p. 9, footnote). The sandy beds of the Double

TABLE 1.—Macrofossils from the Double Corner Shell-beds (Waiauan).

	S 68/ 155	S 68/ 156	S 68/ 157	S 68/ 158	S 68/ 159	S 68/ 160	S 68/ 161	S 68/ 162	S 68/ 163	S 68/ 164	S 68/ 165	S 68/ 166	S 68/ 167
Glycymeris aff. *huttoni* Marw. aff. *hurupiensis* Marw.	×	×	×	×	×	×	×	×	×	×	×	×	
Ostrea cf. *fococarens* Fin.												×	
Eucrassatella ampla(Zitt.)					×								
Pleuromeris aff. *zelandica* (Desh.)													×
Divaricella notocenica King													×
Mylitella n.sp.	×												
Maorimactra acuminella Fin.	×												
Dosinia (*Austrodosnia*) aff. *magna* Hutt.					×						×		×
Dosinia (*Raina*) n.sp.					×	×		×					
Eumarcia aff. *enysi* (Hutt.)		×			×			×	×	×			
Turia waiauensis Marw.	×			×	×			×					
Antisolarium (?) sp.				×				×					
Elachorbis sp.	×												
Zeacolpus n.sp. aff. *pukeuriensis* Marw.		×											
Struthiolaria n.sp. aff. *incrassata* Powell											×		
Maoricrypta radiata (Hutt.)	×		×			×		×	×		×		
Sigapatella alta (Hutt.)	×	×											
Polinices intracrassus Fin.	×	×			×			×	×	×	×		
P. mucronatus (Marw.)	×	×	×	×	×	×		×	×			×	
Taniella notocenica (Fin.)	×												
Polinella cf. *gradisuturalis* Marw.			×										
Chemnitzia sp.	×												
Austrofusus (*Zelandiella*) *fatuus* (Fin.)			×		×	×		×	×	×			
A. (*Zelandiella*) n.sp. aff. *subnodosus* (Hutt.)	×	×	×			×		×	×		×		
Austrotoma aff. *excavata* (Suter)					×			×	×				
A. obsoleta Fin.	×	×	×		×	×		×			×		
Alcithoe oliveri Marw.											×		
Baryspira cf. *novaezelandiae* (Sow.)			×		×			×					
B. subhebera Marw.		×	×	×	×			×	×	×	×		
B. cf. *tholiculus* Marw.													×
Zeacuminia orycta (Suter)	×	×						×					
Dentalium (*Fissidentalium*) aff. *solidum* Hutt.	×	×	×	×	×	×		×					
Tegulorhynchia nigricans (Sow.)							×						
Balanus amphitrite acutus Withers	×		×			×	×		×		×	×	

Corner Shell-beds appear to have been deposited in shallow water which has been subject to considerable wave or current action, that was able to concentrate shells in shell-beds. Probably the environment was that of shallow water off a sandy beach. The *Arachnoides* fragments, as well as some other fossils, were possibly derived from another biotope in a nearby embayment. The absence of pebbles of greywacke indicates that no large river drained into the sea near the lower Waipara Gorge in Waiauan times.

Greenwood Formation

NAME

The bridge across the Waipara River on the Teviotdale Road is named Greenwood's bridge after the owners of Teviotdale station. The name Greenwood Formation is here proposed for the marine gravels, conglomerates, sands, and siltstones cropping out at the "Horse-shoe" and near Greenwood's bridge. It rests unconformably on both the Double Corner Shell-beds and Tokama Siltstone, and is overlain conformably by the non-marine Kowai Gravels.

DISTRIBUTION AND CONTENT

At the base of the Greenwood Formation there are everywhere present several bands of hard pebble and shell conglomerate separated by beds of fine-grained sands. They are well exposed in Wash Creek where there are two conglomerate bands (Fig. 4), and at the "Horse-shoe" where there are three bands (Fig. 5). The conglomerate consists of well rounded greywacke about $\frac{1}{4}$ in. to $\frac{1}{2}$ in. in diameter. There are a few cobbles up to 4 in. through. Shells are abundant but mainly fragmentary and are difficult to extract because of the hardness of the matrix. The conglomerates are strongly cemented with calcite, and a large proportion of the fossils are preserved as casts and moulds. These conglomerate bands are the prominent ridge-forming beds of the district. They crop out on either side of the anticlinal axis. In the south-east limb they form the upper beds of the high escarpment running north-east from the centre of the gorge, crossing the Teviotdale Road, and heading eastwards towards the coast. In the north-west limb of the anticline they are exposed almost continuously following the right bank of the river from the fault half a mile upstream from Greenwood's bridge, to the "Horse-shoe" from where they can be traced upstream along the river for almost a mile. They then cut across Wash Creek and extend as far as Washcreek Road.

The basal conglomerates are overlain by finely stratified interbedded, grey sandstones, siltstones, and mudstones. The strata are mostly about a half inch thick. A few scattered shells were seen in the "Horse-shoe" section where about 350 ft of these alternating beds are well exposed. In Wash Creek they are about 600 ft thick but are poorly exposed in their upper part. They form the right bank of the Waipara River half a mile upstream from the "Horse-shoe".

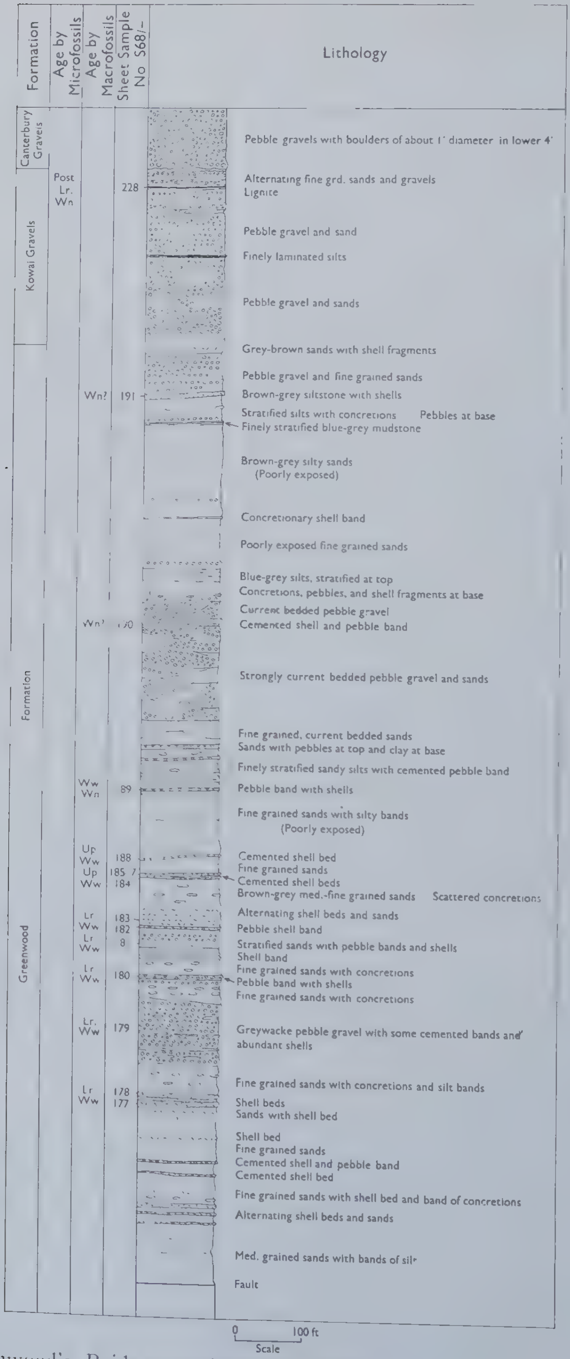
Formation
Age by Microfossils
Age by Macrofossils
Sheet Sample No S68/–
Lithology
Canterbury Gravels
Kowai Gravels
Greenwood Formation
Post Lr. Wn
228
Wn?
191
Wn?
190
Ww Wn
89
Up Ww
188
Up Ww
185 7
184
Lr Ww
183
182
Lr Ww
8
Lr Ww
180
Lr. Ww
179
Lr Ww
178
177
Pebble gravels with boulders of about 1' diameter in lower 4'
Alternating fine grd. sands and gravels
Lignite
Pebble gravel and sand
Finely laminated silts
Pebble gravel and sands
Grey-brown sands with shell fragments
Pebble gravel and fine grained sands
Brown-grey siltstone with shells
Stratified silts with concretions
Pebbles at base
Finely stratified blue-grey mudstone
Brown-grey silty sands
(Poorly exposed)
Concretionary shell band
Poorly exposed fine grained sands
Blue-grey silts, stratified at top
Concretions, pebbles, and shell fragments at base
Current bedded pebble gravel
Cemented shell and pebble band
Strongly current bedded pebble gravel and sands
Fine grained, current bedded sands
Sands with pebbles at top and clay at base
Finely stratified sandy silts with cemented pebble band
Pebble band with shells
Fine grained sands with silty bands
(Poorly exposed)
Cemented shell bed
Fine grained sands
Cemented shell beds
Brown-grey med.-fine grained sands
Scattered concretions
Alternating shell beds and sands
Pebble shell band
Stratified sands with pebble bands and shells
Shell band
Fine grained sands with concretions
Pebble band with shells
Fine grained sands with concretions
Greywacke pebble gravel with some cemented bands and abundant shells
Fine grained sands with concretions and silt bands
Shell beds
Sands with shell bed
Shell bed
Fine grained sands
Cemented shell and pebble band
Cemented shell bed
Fine grained sands with shell bed and band of concretions
Alternating shell beds and sands
Med. grained sands with bands of silt
Fault
0
100 ft
Scale

FIG. 7.—Greenwood's Bridge stratigraphic column. Lower part measured on left bank, and upper part on right bank.

The upper part of the Greenwood Formation is characterized by the presence of considerable thicknesses of shell-beds, and greywacke pebble conglomerates and gravels, interbedded with sands. Fossils are abundant throughout this upper part, which grades down into the alternating sandstones and siltstones. The best section is exposed on both sides of the Waipara River near Greenwood's bridge. Similar beds are present in the upper parts of the "Horse-shoe" and Wash Creek sections, and they form part of the Amberley Hills. The beds exposed on the right bank of the Waipara opposite its junction with Omihi Stream, belong to the upper part of the Greenwood Formation and consist of about 300 ft of brown micaceous sands which contain some pebble bands, beds of siltstone, and shell-beds. Pebble conglomerates crop out in the second gully on the left bank of the Waipara River, downstream from its junction with Omihi Stream, at the axis of a syncline. These pebble gravels and conglomerates form the top of the Wash Creek section and crop out across the river from the end of Stockgrove Road. The same conglomerates crop out on the right bank of the river for about half a mile downstream from Stockgrove Road.

Near the top of the "Horse-shoe" section 700 ft of sands interstratified with pebble conglomerates, shell beds, and siltstones, belong to the upper part of the Greenwood Formation (Fig. 5).

The banks of the river near Greenwood's bridge are composed of rocks belonging to the upper part of the Greenwood Formation. Two sections were measured; the first (Fig. 7) starts on the left bank at the fault half a mile upstream from the bridge, and extends downstream on this bank for about one and a half miles. The second section (Fig. 8) is confined to the right bank and extends from the fault to the south end of Greenwood's bridge. Comparison of the two columns shows the variability of the beds of this formation. About 1400 ft of this formation is exposed in the left bank section, but only 400 ft crops out in the right bank.

RELATION TO UNDERLYING ROCKS

The Greenwood Formation rests on the underlying beds with slight angular unconformity. At the "Horse-shoe" it overlies the Double Corner Shell-beds, and in Wash Creek it rests on the Tokama Siltstone.

PALEONTOLOGY

MACROFOSSILS:—The collections from the Greenwood's bridge sections are listed in Table 2.

A collection was made from a 25 ft pebble and shell conglomerate which forms the base of the Greenwood Formation near the top of the high cliff on the left bank of the river downstream from the "Horseshoe".

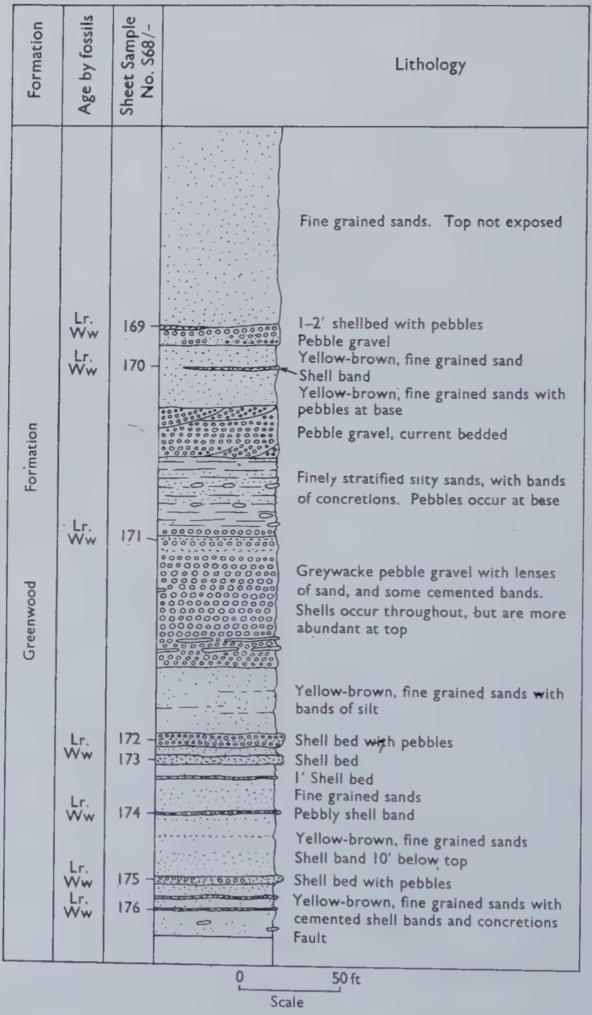
Formation
Age by fossils
Sheet Sample No. S68/-
Lithology
Greenwood Formation
Lr. Ww
169
Lr. Ww
170
Lr. Ww
171
Lr. Ww
172
173
Lr. Ww
174
Lr. Ww
175
Lr. Ww
176
Fine grained sands. Top not exposed
1–2′ shellbed with pebbles
Pebble gravel
Yellow-brown, fine grained sand
Shell band
Yellow-brown, fine grained sands with pebbles at base
Pebble gravel, current bedded
Finely stratified silty sands, with bands of concretions. Pebbles occur at base
Greywacke pebble gravel with lenses of sand, and some cemented bands. Shells occur throughout, but are more abundant at top
Yellow-brown, fine grained sands with bands of silt
Shell bed with pebbles
Shell bed
1′ Shell bed
Fine grained sands
Pebbly shell band
Yellow-brown, fine grained sands
Shell band 10′ below top
Shell bed with pebbles
Yellow-brown, fine grained sands with cemented shell bands and concretions
Fault
0
50 ft
Scale

FIG. 8.—Greenwood's Bridge stratigraphic column on right bank of river upstream from bridge.

S 68/206 GS 5069

Anomia trigonopsis (Hutt.)
Mytilus cf. *canaliculus* Mart.
Ostrea sinuata sinuata Lk.
Coelotrochus sp.
Maurea (*Mucrinops*) aff. *wanganuica* (Oliver)
Maoricrypta radiata (Hutt.)
Balanus sp.
Arachnoides sp.

Age: probably Wanganui Series.

Near the head of a small stream which enters the Waipara on the right bank at the "Horse-shoe", a 12 ft bed of greywacke pebble conglomerate crops out. There is an abundance of well preserved and easily collected Mollusca.

S 68/192 GS 4997
Anomia trigonopsis Hutt.
Glycymeris (*Manaia*) *manaiaensis* Marw.
Ostrea sinuata Lk. (Ribbed form)
Venericardia sp. indet.
Macta (*Cyclomactra*) n.sp. aff. *ovata* (Gray)
Spisula (*Crassula*) n.sp. aff. *aequilateralis* (Desh.)
Chione (*Austrovenus*) sp.
Maurea waiparaensis (Suter)
Zethalia zelandica coronata Marw.
Struthiolaria cf. *errata* Marw.
S. (*Pelicaria*) *zelandiae* Marshall & Murdoch
Maoricrypta radiata (Hutt.)
Zeacrypta monoxyla (Lesson)
Zegalerus tenuis (Gray)
Polinices aff. *pateaensis* (Marw.)
Aeneator aff. *imperator* King
Verconella aff. *haweraensis* (Powell)
V. aff. *mandarina* (Duclos)
Austrofusus (*Zelandiella*) cf. *conoidea* (Zitt.)
Cominella cf. *virgata* H. & A. Adams
C. (*Acominia*) aff. *kereruensis* Laws
C. (*Cominista*) n.sp. aff. *glandformis* (Rve.)
Alcithoe cf. *whakinoensis* Marw.
Otahua cf. *bartrumi* Marw.
Baryspira aff. *mucronata* (Sow.)
Zeacuminia cf. *perplexa* (Marshall & Murdoch)
Crab claws
Balanus sp.
Arachnoides sp.
Age: Waitotaran.

MICROFOSSILS:—The microfaunas from this formation were uniformly poor, and did no more than indicate a Wanganui age. One sample (S 68/142) from Wash Creek yielded a fauna. This was from 43 ft above the base of the formation and contained only *Streblus* which appears as early as Kapitean but becomes abundant in the upper Wanganui Series.

In the "Horse-shoe" section, four samples contained faunas. S 68/149 from 160 ft above the base of the Greenwood Formation yielded a poor fauna with only *Notorotalia hurupiensis* Vella, *Bolivinita pliozea* Finlay, and *Nonion flemingi* Vella, and is probably Wanganui Series but possibly as old as Kapitean. S 68/150 from 350 ft above the base of the formation was similar to 149 but with a poorer fauna. S 68/151 from 370 ft above the base of the formation contained rare *Streblus* and is probably Wanganui Series. S 68/152 from 490 ft above the base of the formation was similar to 151.

AGE AND CORRELATION

The Greenwood's bridge section faunas from S 68/169 to 183 inclusive have been assigned by Dr Fleming to the Lower Waitotaran;

TABLE 2.—Macrofossils from Greenwood's Bridge Section (Waitotaran-Nukumaruan?).

	S 68/169	S 68/170	S 68/171	S 68/172	S 68/173	S 68/174	S 68/175	S 68/176	S 68/177	S 68/178	S 68/179	S 68/180	S 68/181	S 68/182	S 68/183	S 68/184	S 68/185	S 68/186	S 68/187	S 68/188	S 68/189	S 68/190	S 68/191
Linucula n.sp.																							×
Anomia aff. *trigonopsis* Hutt.			×	×		×	×			×													×
Glycymeris manaiaensis Marw.	×		×			×					×	×		×									
G. waipipiensis Marw. ...				×																			
Mytilus canaliculus Mart.				×			×																
Modiolus huttoni Suter																					×		
Phialopecten triphooki (Zitt.)	×		×	×						×	×	×		×									
Mesopeplum aff. *crawfordi* (Hutt.)				×	×					×													
Crassostrea ingens (Zitt.) ...				×		×			×					×						×			
Ostrea s. sinuata Lk.			×	×	×	×	×	×		×	×				×	×	×	×	×	×	×	×	×
O. sinuata cf. *charlottae* Fin.										×				×									
Lasaea n.sp.													×										
Melliteryx aff. *parva* (Desh.)		×																					
Barytellina sp. indet. ...																						×	
Mactra (*Cyclomactra*) sp. ...													×	×									
M. (*Cyclomactra*) cf. *ovata* (Gray)		×				×																	
M. (*Cyclomactra*) cf. *tristis* Reeve																							×
Lutraria solida Hutt.	×		×								×	×		×	×								
Dosinia (*Austrodosinia*) sp.																							×
D. (*Phacosoma*) sp.												×			×								
Tawera sp.											×	×		×									
Bassina yatei (Gray)																							×
Chione stutchburyi (Gray) subsp.																							×
Eumarcia (*Eumarcia*) *kaawaensis* Marw.												×											
E. (*Eumarcia*) *plana* Marw.														×									

Anchomasa similis (Gray)													×										
Myadora boltoni Smith																							×
M. striata (Q. & G.) subsp.																							×
Coelotrochus n.sp.											×												
C. sp. indet.																							×
Maurea cf. *hodgei* (Hutt.)																							×
M. aff. *punctulata* aff. *spectabile*	×										×												
M. waiparaensis (Suter)			×								×	×		×									
Zethalia zelandica coronata Marw.															×								
Dardanula (?) sp.													×										
Zeacumantus n.sp. aff. *lutulentus* (Kiener)													×										
Zeacolpus (*Stiracolpus*) aff. *symmetricus* (Hutt.)			×								×	×											
Struthiolaria firthi Marwick		×																					
Maoricrypta radiata (Hutt.)	×										×												
M. sp. indet.		×															×		×				
Sigapatella sp. indet.		×										×											
Polinices waipipiensis (Marw.)		×																					
Friginatica marshalli Marw.											×												
Verconella haweraensis Pow.	×																						
V. aff. *allani* Fin.	×																						
Alcithoe aff. *swainsoni* Marw.	×																						
Baryspira aff. *mucronata* (Sow.)	×	×										×											
B. cf. *opima* (Marw.)													×										
Pervicacia cf. *tristis* (Desh.)		×																					
Crab (undetermined) ...												×											
Balanus amphitrite acutus Withers											×											×	
B. amphitrite communis Withers										×	×		×	×	×	×	×	×				×	
B. cf. *decorus* Darwin ...				×																			×
B. tubulatus Withers ...				×								×											
B. (undetermined)	×		×			×	×	×				×							×	×			×
Arachnoides sp.				×				×		×					×				×				
Polyzoa (undetermined) ...				×	×					×													

those from S 68/184 to 188 tentatively to the Upper Waitotaran; and those from S 68/190 and 191 tentatively to the Nukumaruan. The assignment of collections S 68/169 to 183 to the lower substage of the Waitotaran is based on the "presence of *Crassostrea ingens*, *Phialopecten triphooki*, *Mesopeplum* aff. *crawfordi*, and *Glycymeris manaiaensis*. . . . The presence of *Polinices waipipiensis*, *Friginatica marshalli*, *Verconella haweraensis*, *Zethalia z. coronata*, and *Eumarcia* cf. *healyi* . . . reinforce the age determination. The presence of *Stiracolpus* aff. *symmetricus* is in accord with our inference that the Waitotaran of Canterbury contains a cool water element which did not reach the central North Island until the early Nukumaruan." (Dr C. A. Fleming, pers. comm.) Dr Fleming has assigned samples S 68/184 to 188 to the Upper Waitotaran, but there is little evidence for such an age other than the absence of large pectens and *Glycymeris manaiaensis*. The highest samples S 68/190 and 191 may be Nukumaruan, but the faunas are too small to be sure. "*Chione* is rare in the Waitotaran, but this is certainly due to facies. The Waipara form is not the Otahuhu *Chione tamakiensis*, but this means nothing as we know little of the pattern of geographic races at that time; the *Cyclomactra* is also different from the Otahuhu Waitotaran forms. Both *Myadora* species are found in the Nukumaruan, and *Maurea hodgei* has not been recorded prior to that stage." (Dr C. A. Fleming, pers. comm.)

The faunas from the Greenwood Formation indicate that it ranges in age from Waitotaran to possibly Nukumaruan, and hence can be correlated with the lower part of Mason's (1941, p. 122-5) Kowhai Series at Mount Grey; and with Thomson's (1920, p. 363-6) Motunau or Greta beds in the Middle Waipara and Weka Pass.

CONDITIONS OF DEPOSITION

The Greenwood Formation contains an abundance of greywacke pebbles, in contrast to their absence in the underlying formations. The basal conglomerates, which contain many worn and fragmental shells, indicate deposition in an environment where the sediments were subject to strong current action, and are presumably a near-shore deposit. The large thickness (some hundreds of feet) of uniformly stratified sandy siltstones and mudstones overlying these conglomerates indicates deposition which continued for some time in water not disturbed by strong currents; this and the absence of shell-beds in these strata suggests deposition at some distance from a shore-line.

The faunas, as well as the lithologies, of the beds of the Greenwood's bridge section are rather diversified. The most common type of shell-bed is one that contains *Ostrea sinuata*, *Balanus*, and sometimes *Arachnoides*, *Anomia* aff. *trigonopsis*, and *Maoricrypta*. This fossil assemblage usually occurs in cemented shell-beds that contain a larger percentage of shells than matrix. These beds occur at many places in the section. They commonly contain *Ostrea* with closed valves, so presumably the shell bed was the habitat of the animal. A variation of this type of bed is one which has in addition *Phialopecten triphooki* and *Mesopeplum* aff. *crawfordi* as well as other bivalves. Another type of bed is the greywacke pebble conglomerate or gravel containing shells. These beds usually contain abundant *Glycymeris manaiaensis;* often, however, these shells are very worn. Common ,also, in this type of bed, are *Phialopecten triphooki*, and *Lutraria solida*, and sometimes *Ostrea sinuata sinuata* and *Maoricrypta*. In places there is a local abundance of *Tawera* or *Stiracolpus*. Many of the thinner bands of pebbles contain a somewhat similar fauna with, however, a great abundance of *Maurea waiparaensis* and *Crassostrea ingens*. The *Glycymeris* in these conglomerates appear to have been derived from another biotope but the other shells appear to have lived on the gravel sea-bottom.

The beds of the Greenwood's bridge section appear to be all of shallow-water origin. The fauna from S 68/181, which was collected from near the top of 30 ft of stratified medium-grained sands, is interesting in that it contains two intertidal forms; *Anchomasa,* a rock-borer that lives on intertidal rock platforms; and *Zeacumantus* which is found on intertidal sand-flats. The only other collection that contains forms indicating an intertidal environment is S 68/191; *Chione stutchburyi* is characteristic of enclosed tidal mud flats and ranges from half-tide to low-tide and occasionally to a depth of two fathoms (Powell, 1947, p. 22); *Myadora striata* and *Myadora boltoni* occur in sands at, and below, low-tide level (Powell, 1946, Pl. 10). This fauna, S 68/191, was collected from a grey slit that is the highest exposed bed on the left bank of the river, and consists mainly of pelecypods with closed valves, which are difficult to extract from the matrix.

The majority of the faunas present in the Greenwood's bridge section appear to have lived either in sands below low-tide level, or on hard bottom which was suitable for the growth of the *Ostrea-Anomia* beds that are common in the section; this hard bottom probably resulted from the activity of currents that were sufficiently vigorous to by-pass sediment.

Kowai Gravels

NAME

The name Kowai Series was proposed by Speight (1919) for the tilted gravels, well exposed in the Kowai River. Speight included marine beds at the base of his formation, but the bulk of the beds were non-marine. Thomson (1920, p. 366) restricted the name Kowhai (*sic*) Series to the non-marine gravels. Mason (1941, p. 122-5) reverted to Speight's original usage by including Waitotaran shell-beds at the base of the Kowhai Series. The name Kowhai Gravels was first used by Henderson (1930, p. 291). The name Kowai Gravels is adopted in this paper, and is used in Thomson's restricted sense for non-marine beds. "Kowai" is the spelling used on current Lands and Survey maps.

DISTRIBUTION AND CONTENT

The Kowai Gravels form much of the Amberley Hills, and extend underneath younger gravels to the south-east to crop out on the right bank of the Waipara River for about one mile upstream from Webbs Road. Their distribution in the Amberley Hills, as shown on the geological map, is inferred from a few outcrops only.

Kowai Gravels, 300 ft thick, exposed along the right bank of the river form the upper part of the sequence at Greenwood's bridge (Fig. 7). The formation is predominantly gravels, but there are lenses and beds of sands and silts. A 3 ft bed of finely laminated silts crops out at S 68/134034; the laminations in this, apparently lacustrine silt, are very uniform and about 1/32 in. thick. Near the top of the formation, lignite beds occur. The river flows along the strike of the beds and lignite is found at various places for about half a mile along the bank of the river. Over this distance a one foot band of lignite near Webbs Road splits into two six inch bands separated by one foot of clay. At both places it is associated with sands and clays containing pieces of lignite and lignified wood. The lignite was mentioned by Torlesse (in Maling, 1958, p. 130) and Haast (1879, p. 318), and the section which contains it, was described by Speight (1919, p. 279).

In the Amberley Hills 80 ft of Kowai Gravels are exposed about a quarter of a mile east of Trig. G. Beneath these gravels which are dipping at 20° to the south, are sands with a poorly preserved molluscan fauna.

The total thickness of the Kowai Gravels can be only roughly estimated. Judged by the few exposures present on the Amberley Hills, the thickness is about 1000 ft.

The material making up the gravels is largely greywacke pebbles similar to those in the Waipara River bed today. No pebbles of Tertiary rocks were seen, but pebbles of igneous rock occur.

RELATION TO UNDERLYING ROCKS

The Kowai Gravels grade downwards into the Greenwood Formation, and the dividing point between the two formations has been taken at where sediments containing shells and shell fragments pass up into sands and gravels bearing no trace of marine origin.

PALEONTOLOGY

MICROFOSSILS:—A sample of the lignite (S 68/228, L 1017) from the Kowai Gravels in the Greenwood's bridge section has been examined by Dr R. A. Couper. The flora shows that it is definitely younger than Lower Nukumaruan; it could be Upper Nukumaruan, but there is no definite evidence for this age (Dr R. A. Couper, pers. comm.).

AGE AND CORRELATION

The top of the underlying Greenwood Formation may be Lower Nukumaruan. The flora from the lignite of the Kowai Gravels in the Greenwood's bridge section suggests Nukumaruan, and hence the Kowai Gravels in the lower Waipara Gorge are tentatively assigned to the Nukumaruan. A microfloral sample (S 68/504, L 459) from the type Kowai Gravels is probably Lower Nukumaruan (Couper and McQueen, 1954, p. 418).

The Kowai Gravels of the lower Waipara Gorge can be correlated with the Kowhai Series of Thomson (1920) in the middle Waipara, and with the upper part of the Kowhai Series of Mason (1941) in the Mount Grey District.

CONDITIONS OF DEPOSITION

The absence of shell material from such a large thickness of beds is in marked contrast to its abundance in the formations which underlie them. The Kowai Gravels are probably a deposit of fluviatile origin with possible lacustrine and estuarine phases.

Late Pleistocene Gravels

The late Pleistocene gravels of the lower Waipara Gorge can be divided into two formations, the gravels capping the Teviotdale Terrace of Jobberns (1937, p. 129-31), and the Canterbury Gravels (Wilson, 1955) forming the Canterbury Plains.

GRAVELS FORMING THE TEVIOTDALE TERRACE

Jobberns (1937, p. 129) named the Teviotdale Terrace and described it as being best developed on the north side of the Waipara River, extending from the gorge to near the present shore. He believed that it once extended across the Amberley Hills and correlated it with terrace remnants about the south-eastern base of Mount Grey. The gravels underlying the Teviotdale Terrace are brown in colour, being more weathered than the younger gravels. They rest unconformably on the older formations.

The maximum thickness is unknown but may be a hundred feet or more.

The gravels have been deposited during a period of fluviatile aggradation.

CANTERBURY GRAVELS

The Canterbury Gravels were named by Wilson (1955) and underlie his Canterbury Surface. They abutt the Amberley Hills on all sides except the north-east. Part of the surface they form was named the Amberley Terrace by Jobberns (1937, p. 128-9). The seaward boundary is a cliff extending south-west from near the mouth of the

Waipara River where it is about 70 ft high. It continues for several miles to the south-west and steadily decreases in height. The Canterbury Gravels are less weathered than the gravels underlying the Teviotdale Terrace, but are more weathered than the Holocene gravels.

The Canterbury Gravels are 60 ft thick at Webbs Road, near the mouth of the Waipara River (Fig. 7). Their maximum thickness is unknown. They rest unconformably on older formations.

The gravels have been deposited during a period of fluviatile aggradation, and were correlated by Wilson (1955) with the last major advance of the Last Glaciation.

Holocene Deposits

The Holocene gravels form the river-flats. The pebbles are predominantly greywacke, but contain a higher proportion of Tertiary rocks than the gravels underlying the Teviotdale Terrace, and Canterbury Surface. The Amberley strand-plain, named by Jobberns (1937, p. 126-7) lies between the Canterbury Surface and the coast. This plain has been formed by retreat of the sea, following the Flandrian transgression, and is composed mainly of sands.

Small sand dunes are present near the south sides of the high cliffs flanking the Waipara River. In the cliffs unconsolidated Tertiary sands crop out and are eroded and redeposited by the strong north-west winds that sweep through the gorge in the summer months.

STRUCTURE

The main structural feature of the lower Waipara Gorge is an asymmetrical anticline that extends from the Mount Cass Range in the north-east to the Amberley Hills in the south-west. This fold is flanked to the north-west by a minor parallel syncline. Both folds plunge to the south-west. Speight (1912, p. 227-30) recognized both these folds. The flanks of the anticline are to some extent disrupted by two reverse faults parallel to the anticlinal axis.

A reverse fault of about 200 ft throw cuts across the spur which forms the "Horse-shoe". The fault plane strikes at 025° and dips at about 60° to the west. Strata of the Double Corner Shell-beds and Greenwood Formation are repeated by the fault which can be traced for one mile to the south-west of the "Horse-shoe", and for about half a mile to the north-east.

Another fault cuts across the river half a mile upstream from Greenwood's bridge, and is probably that referred to by Hector (1869, p. xii). The strata adjacent to the fault on both banks of the river are much disrupted. The fault appears to have a displacement of about 100 ft stratigraphically. It could not be traced beyond the exposures in the banks of the river.

TABLE 3.—Fossil Samples.

Sheet Sample No.	Register No.	Grid Reference
S 68/137	F 9602	148099
138	F 9603	145096
139	GS 4924 F 9604	143095
140	F 9612	142095
141	*	142095
142	F 9610	142095
143	*	141096
144	F 9605	135076
145	*	134076
146	*	134076
147	*	133076
148	*	132075
149	F 9606	132075
150	F 9607	131075
151	F 9608	131075
152	F 9609	130075
153	*	130075
154	*	129075
155	GS 4911	132077
156	GS 4912	132077
157	GS 4913	132077
158	GS 4914	132077
159	GS 4915	132077
160	GS 4916	133077
161	GS 4917	133077
162	GS 4918	134076
163	GS 4919	134076
164	GS 4920	134076
165	GS 4921	134076
166	GS 4922	135076
167	GS 4923	135076
169	GS 4938	137050
170	GS 4939	137050
171	GS 4940	133053
172	GS 4941	132054
173	GS 4942	132054
174	GS 4943	132055
175	GS 4944	132055
176	GS 4945	132055
177	GS 4946	138054
178	GS 4947	138053
179	GS 4948	138052
180	GS 4949	140051
181	GS 4950	141050
182	GS 4951	141049
183	GS 4952	141049
184	GS 4953	141047
185	GS 4954	141047
186	GS 4955	141047
187	GS 4956	141047
188	GS 4957	141047
189	GS 4958	141045
190	GS 4959	139041
191	GS 4960	139035
192	GS 4997	122069
206	GS 5069	138074
228	L 1017	134028

*Microfaunal sample with no fauna.

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THE STRUCTURE OF THE LOWER MESOZOIC ROCKS IN THE PORIRUA DISTRICT

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Summary

The well indurated greywacke-argillite rocks of the Porirua district have been subjected to strong folding followed by more than one period of intense faulting and fracturing. The main axis of flexural folding trends NNE-NE and plunges 14° to 17° NE. Numerous small-scale folds are described. They exhibit a wide range of forms: from open, symmetrical, and faulted folds to isoclinal folds. A few localized folds, described as incongruous, have axes that cut across the NNE-NE trending regional fold axis.

Faults are classified, on the basis of certain field criteria, into two broad age groups, early and late. The early faults include those associated with folding and those formed during subsequent episodes of faulting. Late faults comprise those that have been active during and possibly somewhat prior to the Quaternary.

INTRODUCTION

The alternating greywacke and argillite strata in the Porirua district are well indurated, intensely fractured, and have a predominant strike varying from 10° to 50° east of north (Fig. 1). Generally the strata are steeply dipping and commonly overturned. Bed facings (Webby, 1959) are predominantly to the west. Numerous small-scale folds, observed in coastal sequences near Titahi Bay, indicate that the rocks are tightly folded. Since their folding, the rocks have been subjected to faulting of more than one age.

Quennell (1938) described a number of faults in the Porirua district, on the basis of their geomorphic expression. One of these, the Owhariu Fault, has subsequently been referred to by Adkin (1951; 1954), Lensen, Stevens and Wellman (1956), and Lensen (1958).

FOLDING

Statistical analyses, by a method developed by Sander (1948), and used by Weiss (1954) and Brothers (1956), have revealed that there is a single fold axis* in the Porirua rocks west of the Owhariu Fault. The intersections of bedding planes were plotted on a lower hemisphere projection of an equal area net, and the density of distribution of plots contoured (Fig. 2a). The pronounced maximum, which represents the

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*The fold axis is defined by Wegmann (1929) and re-stated by Clark and McIntyre (1951, p. 594) as follows: "The axis of a fold is defined as the nearest approximation to the line, which, moved parallel to itself in space, generates the fold."

N.Z. J. Geol. Geophys. 2. 528-40.

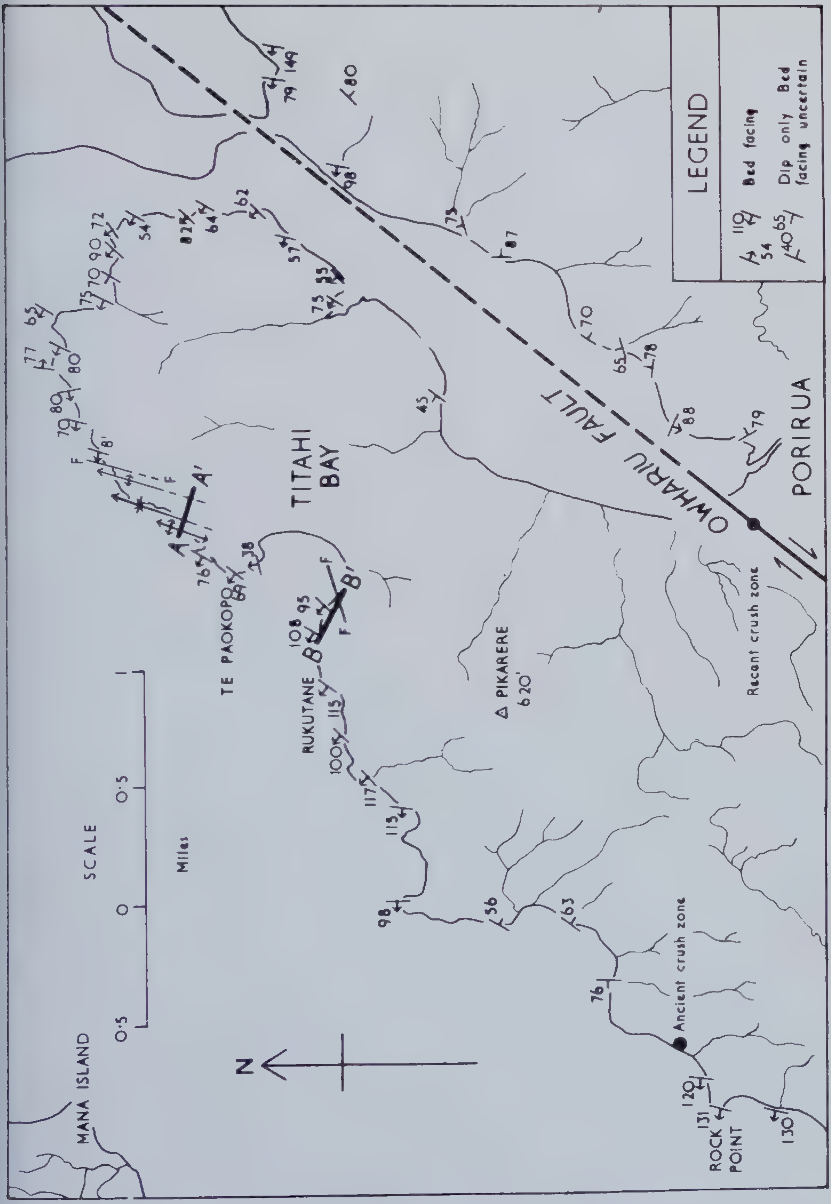

FIG. 1.—Map of the Porirua district showing the location of the cross-sections and structural features mentioned in the text.

fold axis, trends 040° and plunges 17° NE. The poles of bedding planes were also plotted, and a great circle drawn through their maximum density (Fig. 2b). The fold axis is represented by the pole of the great circle. It trends 034° and plunges 14° NE. Similar trends and

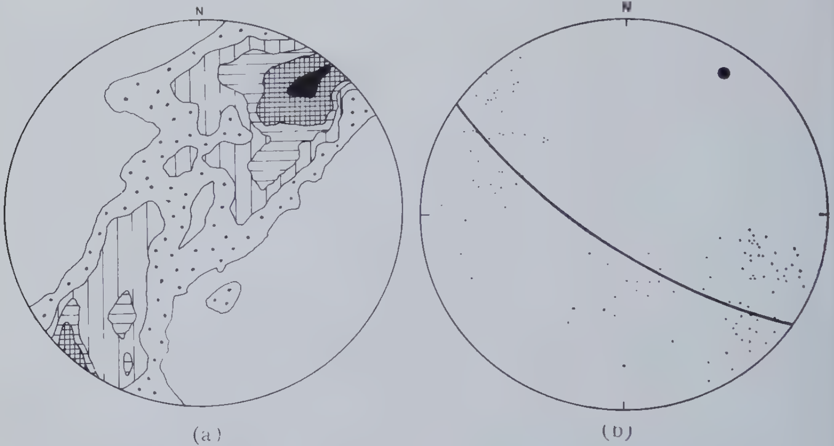

FIG. 2(a).—Contour diagram of the intersections of bedding planes at Titahi Bay, calculated on 2,145 plots. Contours at 9%, 5%, 3%, 2%, and $\frac{1}{2}$% per 1% area.

FIG. 2(b).—Lower hemisphere projection of poles of bedding planes at Titahi Bay. 128 plots.

plunges are recorded from the majority of small-scale folds (see below).

The pattern of folding is illustrated by WNW-ESE cross-sections: A-A′ to the north, and B-B′ to the south of Titahi Bay (Fig. 3). These cross-sections were constructed from detailed mapping of coastal exposures and actual observation of the folds. In both cross-sections the strata are strongly folded, although more strongly in B-B′ than in A-A′. The folds plunge gently NE, and have axial planes that are almost vertical in cross-section A-A′, and dip 60° to 70° SE in cross-section B-B′.

Description of Folds

The folds described in the following account are arranged in an approximate order of increasing complexity.

An open, symmetrical and faulted anticline is exposed along the coast, north of Titahi Bay (Fig. 3, F1; Fig. 4). The plunge of this fold gradually changes when traced for 250 yards along its trend. Towards the north the fold axis has a gentle NNE plunge, and to the south a gentle SSW plunge. The fold flexes a sequence of thick graded beds intercalated with thin beds. During folding the zones of thin beds, which contain wavy bedding and bedding-plane faulting, were relatively incompetent between the thick, competent beds.

A faulted, slightly asymmetric syncline (F2), more strongly folded than F1, was observed 35 yards east of anticline F1. The syncline trends 020° and plunges 10° NNE.

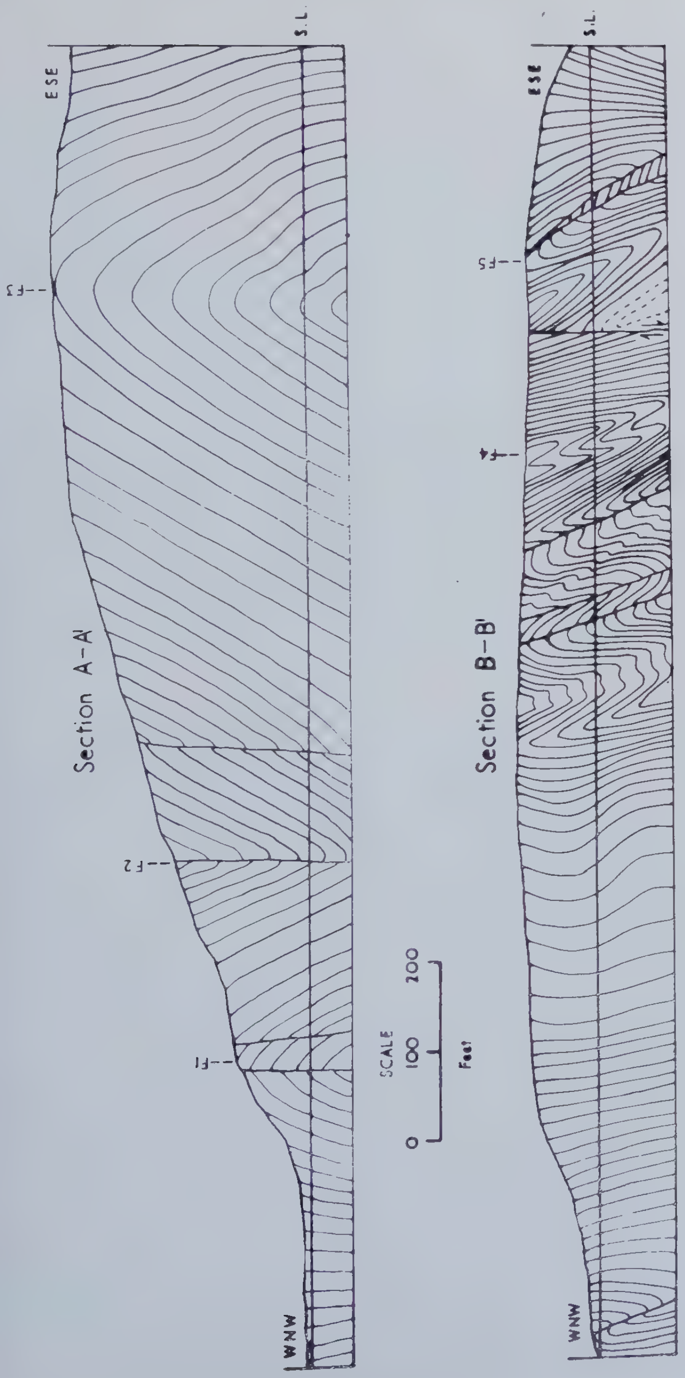

FIG. 3.—Cross-sections north (A-A'), and immediately south (B-B') of Titahi Bay, showing the pattern of folding and faulting. All folds and faults represented in these cross-sections were observed in the field.

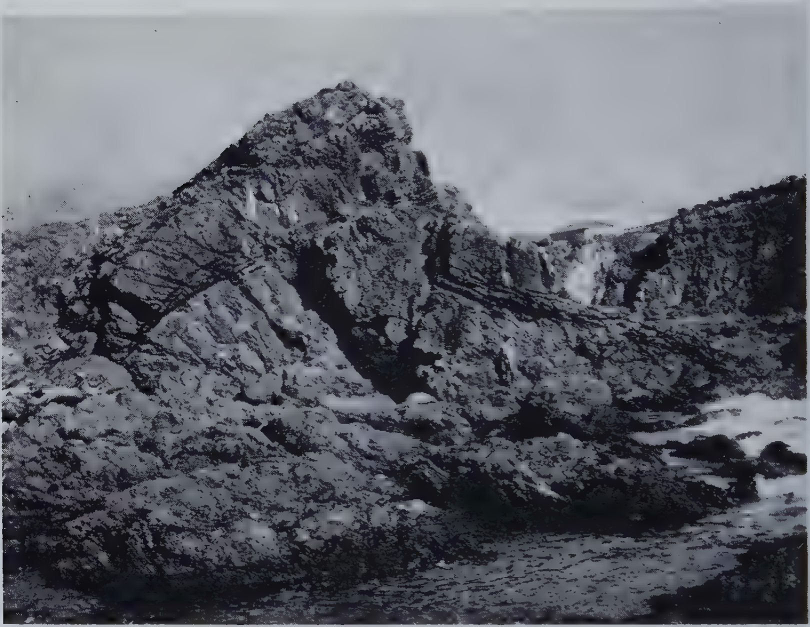

FIG. 4.—An open, symmetrical and faulted anticline (F1) exposed on the coast north of Titahi Bay.

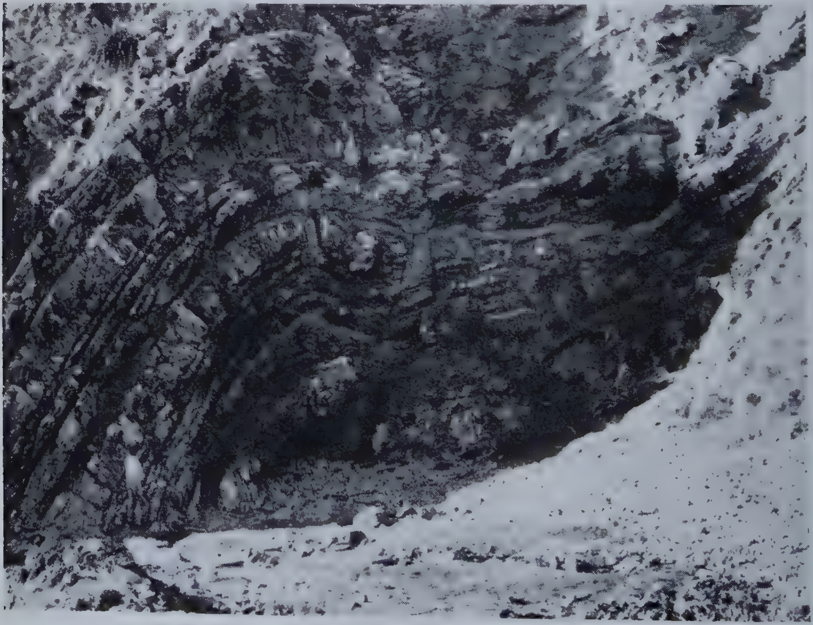

FIG. 5.—An S fold exposed at Te Paokopo.

Syncline F2 is followed, approximately 150 yards eastwards, by another open, symmetrical anticline (F3). The anticline, which occurs in thick graded beds, has a gentle NNE plunge. Between F2 and F3 there is a minor faulted S fold.

An S fold is exposed in the coastal cliff at Te Paokapo, near Titahi Bay (N160/387445) (Fig. 5). The axial plane of this fold dips steeply east, and the plunge is 5° NNE. Fracturing and small-scale faulting are particularly noticeable in the flexed portion of the S fold.

Nearby, another S fold crops out (N160/388442), more strongly folded and recumbent with an overturned middle limb. The fold plunges gently NNE, and the axial plane dips 20°E. A small fault dipping 55° E parallels the bedding in the overturned limb.

A small compact S fold (Fig. 6) was observed at Rock Point (N160/347408). The fold occurs in very thin overturned strata. Its axis has a 015° trend, no plunge, and its axial plane dips 72° E.

A typical example of the tight folding which characterizes the thinly bedded strata on the coast south of Titahi Bay is a narrow, asymmetric syncline (Fig. 3, F4; Fig. 7). Its axis trends 043° and plunges 25° NE. The axial plane of the fold dips steeply (66° SE). The south-eastern flank of the fold is overturned and dips 79° SE, and the north-western flank dips 54° SE.

The tightest folding observed is represented by a rather complex fold (F5), which is also exposed in the thin graded beds on the coast south of Titahi Bay (Fig. 8). The strata are overturned on both sides of the fold, as deduced from a careful study of graded bedding. Thus, the structure is a plunging, asymmetric, faulted S fold. Both anticlinal and synclinal portions of the S fold are complicated by faulting.

Incongruous Folds

A few folds in the region west of the Owhariu Fault have axes that cut across the NNE-NE trending regional fold axis. Two of these were studied in detail. The axis of an S fold exposed north of Titahi Bay (N160/388446) trends 065° and plunges 20° W, and is surrounded by strata that strike NE and dip 70° to 80° NW. Field observation of the fold suggests that it developed prior to regional folding about a NNE-NE trending axis. If this is so, then the fold originally had a recumbent form, an axis with a trend of about 070° and a gentle plunge to the east.

Another S fold is situated between the anticline F1 and the syncline F2, on the coast north of Titahi Bay (N160/391449). This fold has a vertical axis. The axial planes of the S fold, as seen on the coastal wave-cut platform, strike 160°. Eastwards across the trough of syncline F2 there is an intensely deformed zone. This zone may represent a continuation of the S fold present in the eastern flank of syncline F2. In this area, the regional folding was probably superimposed on an

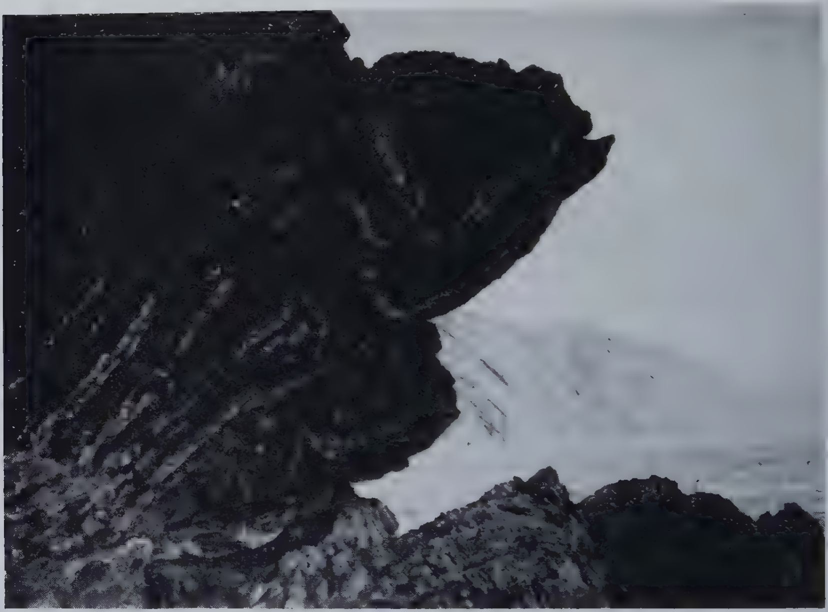

FIG. 6.—An S fold exposed at Rock Point.

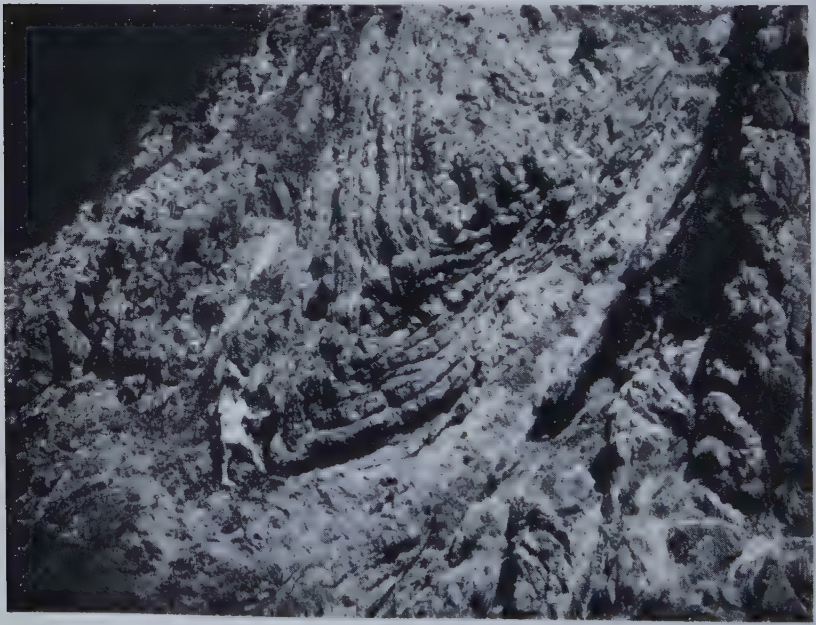

FIG. 7.—A syncline (F4) exposed on the south coast of Titahi Bay.
Professor R. H. Clark, photo

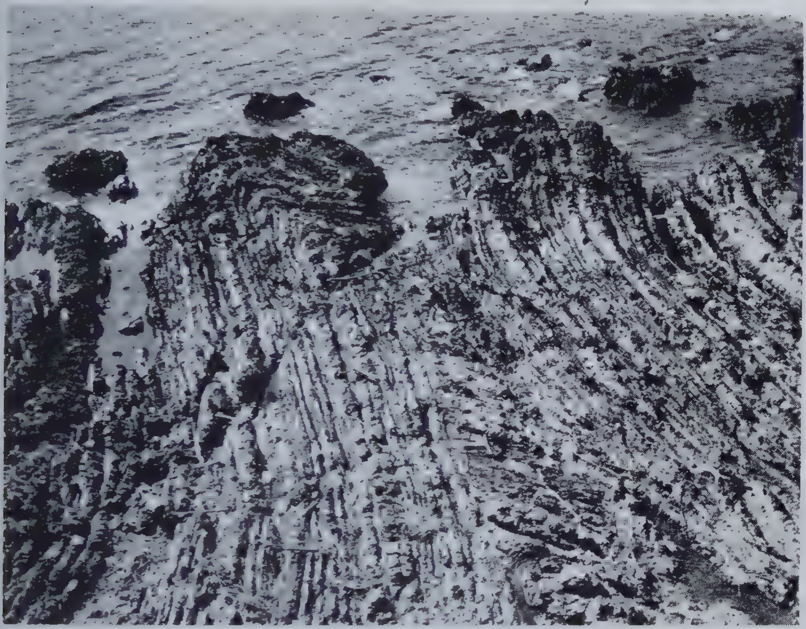

Fig. 8.—A faulted S fold (F5) exposed on the south coast of Titahi Bay.

earlier recumbent overfold, the axis of which had an original NW trend and little or no plunge.

Features Associated with the Folding

The sediments, which have formed greywacke and argillite respectively, have possessed differing degrees of competency under a uniform stress condition. In a graded bed, the greywacke unit (relatively competent) has been folded mainly by concentric shear along bedding planes, as shown by slickensiding and bedding plane faults. The argillite unit (relatively incompetent) has been folded mainly by irregular slip along a multitude of parallel shear planes oblique to bedding—*fracture cleavage.*

Discussion of Folding

Notwithstanding the localized nature of the area studied, the exposed folds exhibit wide variations in shape and size. If a uniform stress condition acted during the folding, variations in shape and size may be the result of differential competencies in the rocks. For example, the broad, open folds F1, F2, and F3 are developed in thick beds interspersed with thin (relatively competent), and the tight folds shown in cross-sections B-B′ are in thin graded bedding (relatively incompetent).

Alternatively, the folds may vary in shape and size because during folding differential stresses acted on the beds undergoing deformation.

The exposed folds also exhibit small variations in orientation. Some of these may be the result of subsequent faulting and associated tilting. It was noted that the axes of the folds at the coast south of Titahi Bay plunge up to 25° NE, and north of Titahi Bay axes of folds usually plunge 15° NNE. Differential tilting associated with recent faulting, as deduced from the present surface expression of K Surface remnants (Cotton, 1957) directly north and south of Titahi Bay, may account for at least 5° of the difference in plunge.

In general, the folds exhibit a range of forms from concentric folds displaying fracture cleavage in the argillite to isoclinal folds. Most of the slip during folding was along bedding planes, and to a lesser extent along a multitude of internal shear planes in the argillites.

At present only a very tentative explanation for the origin of the incongruous S folds can be given. The folds are small, localized, originally recumbent and with varying original axial trends. These four factors, when considered collectively, suggest that the incongruous folds originated by gravity slumping. The type of slump fold envisaged is a "paralloid fold" (Waterhouse and Bradley, 1957). Another possible interpretation for their origin is by overthrusting. The localized nature of the folds, however, and the varying trends are opposed to this latter view.

There are few detailed accounts of "Alpine Facies" folds available for comparison. Brodie (1953) described a large inverted overturned syncline on the south coast of the Wellington Peninsula. Recent observations by Waterhouse (1955), and Lillie, Gunn, and Robinson (1957) in the Southern Alps indicate isoclinally folded strata mainly trending between NNE and NE. The major isoclinal folds from the Alpine region, though on the whole larger, have a form directly comparable with numerous folds described in this account.

FAULTING

The faulting is classified as either early or late, on the basis of field criteria. Early faulting is indicated by indurated autoclastic breccias, cemented fault planes, and stretched and bent bedding adjacent to faults. In contrast, late faulting is indicated by soft pug in crush zones, fault planes not cemented, bedding sharply truncated by faults, weathered and unweathered strata in fault contact, faulted superficial (Quaternary) deposits, and the geomorphic expression of recent faults. Brodie (1953) also distinguished two periods of faulting in the greywackes and argillites on the south coast of the Wellington Peninsula.

Numerous small-scale lateral fault displacements were measured in *vertical* strata near Titahi Bay. These have been grouped, on the above field criteria, as early or late. In addition, displacements have been classed as sinistral or dextral, on the assumption that the faults were transcurrent. The results are shown graphically in Fig. 9. It must be stressed that where faults strike between 010° and 055° (predominant

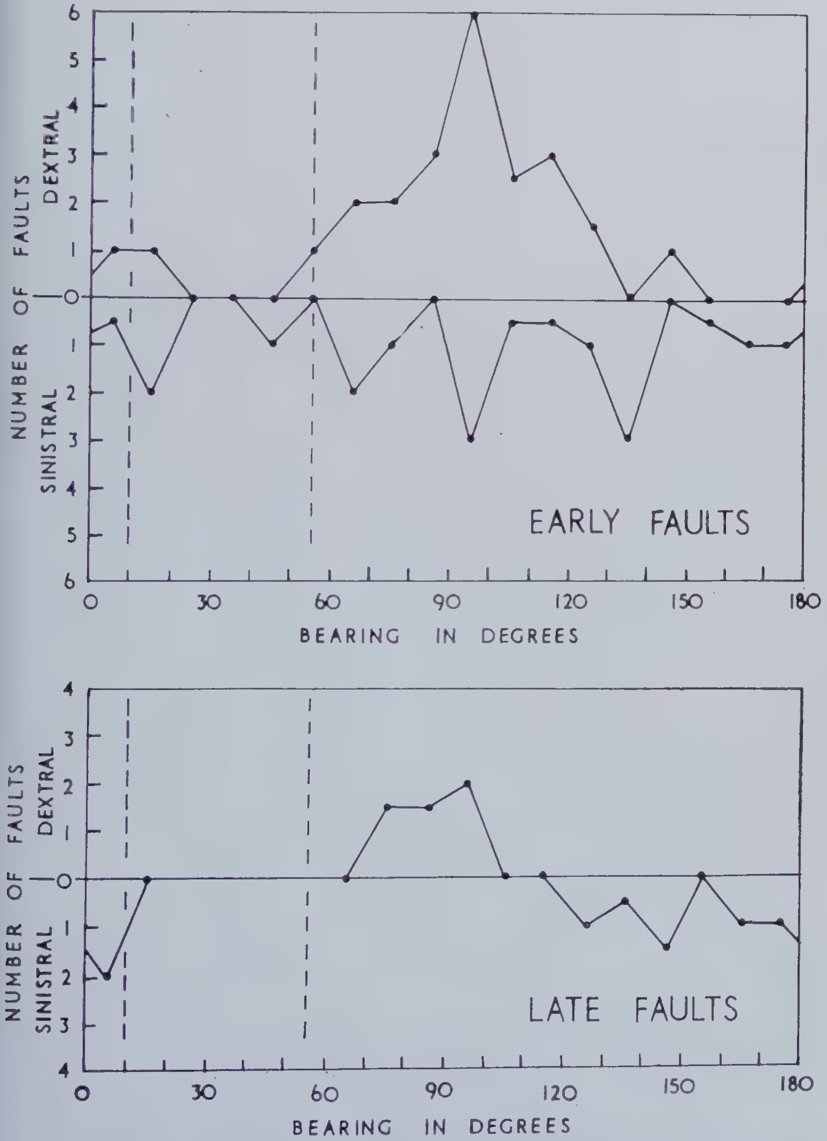

FIG. 9.—Frequency polygons of early and late small-scale lateral faults in *vertical* strata. The bearing and nature of these faults (i.e. dextral or sinistral) is shown. Note that the predominant strike of bedding is between the dotted lines.

strike of strata) no displacements can be observed, as such faults are parallel to bedding. Hence, though such faults may be observed, they cannot be represented in the graphs because the nature of their displacements is unknown.

The late faults are transcurrent, and fall into two groups: those with strikes between 65° and 105° are dextral; those with strikes between 115° and 195° are sinistral. It is probable that there are many late, dextral faults which parallel the strata, unrepresented in the graph. The graph of early faults does not show a pattern consistent with transcurrent faulting. It is suggested that these faults developed prior to a major rotation of the strata into a vertical attitude.

Description of Early Faults

Bedding plane faulting is commonly present in the alternating strata. Such faults are usually situated in the argillite units, near the abrupt contacts between successive graded beds. Bedding plane faults may have narrow crush zones up to 8 cm wide that have been cemented with quartz.

A coastal cliff explosure just east of Rock Point (N160/352413), contains an indurated autoclastic breccia, which may have developed in a crush zone of a large ancient fault (Fig. 1). The autoclastic breccia is almost as thoroughly indurated as typical Wellington greywacke, and is composed of irregular crudely aligned angular fragments of (vein) quartz and greywacke (pebbles up to 5 cm diameter). In the region associated with the autoclastic breccia, the greywackes and argillites contain numerous veins of quartz and some of calcite.

Veining

Veins* are generally rare in the greywacke-argillite rocks of the Porirua district, but are not uncommon in localized areas formerly subjected to intense shearing. The veins are up to 6 cm thick and contain quartz or, rarely, calcite.

Veinlets are fairly common in the rocks, particularly in the greywackes. They are heavily concentrated in localized areas. Veinlets studied in thin section contain mainly quartz. A few veinlets of prehnite were also recognized. Brothers (1956, p. 478) noted that "prehnite typically occurs in sandstone members of the Auckland rocks where solutions rich in Ca and Si, ———, have crystallized in tension fractures".

Description of Late Faults

In the Porirua district numerous late faults were observed, from the small-scale displacements of graded beds, to the "major" transcurrent

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*An arbitrary figure of 1 cm is taken as the thickness boundary between veins and veinlets.

Owhariu Fault (Lensen, 1958) with a crush zone 200 ft in width.

The exposed crush zone of the Owhariu Fault (Fig. 1) consists of extensively shattered and brecciated rock fragments incorporated in a soft blue pug. Large elongated slivers of brown weathered greywacke were observed in the pug. The presence of these infaulted slivers within the crush zone confirms that the movements were comparatively recent. The slivers are irregularly aligned in a direction parallel to the topographic expression of the Owhariu Fault.

On the coast south of Titahi Bay, a small fault (which cuts across the line of section B-B′—see Fig. 1) has brought weathered and fresh rock into juxtaposition along the fault plane. The fault is vertical, and it strikes 057°. The estimated throw is 30 ft with the downthrown side to the SE.

DISCUSSION OF FAULTING

Early faulting accompanied the regional folding and was followed by further episodes of early faulting which produced the autoclastic breccia and some faults with cemented fault planes. Brodie (1953, p. 223) pointed out that the greywacke-argillite rocks at the south coast of the Wellington Peninsula, which were subjected to early faulting, must have been "buried deeply enough to permit cementation of the shattered rock with networks of quartz veins and to allow complete induration of the shattered material". The Porirua rocks were probably similarly buried during the early faulting period. In general, the folding and early faulting in the Porirua district may be considered to belong to the widespread deformation known as the post-Hokonui Orogeny.

Between the early faulting period and the late faulting period there was a large time interval, possibly represented in the Porirua district by a reduced intensity of deformation, and perhaps rotation of strata.

Late faults have been active at least during the Quaternary (Webby, 1958). Small-scale late faulting is probably directly related to transcurrent movement on "major" faults such as the Owhariu Fault.

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GEOLOGY OF THE KAMO MINE AREA

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Summary

Detailed revision of geologic maps, sections, and columns of Kamo Mine area are based primarily upon the interpretation of fieldwork and drilling, both before and after the complete flooding of New Kamo Mine in November 1955. The Kamo Coal Measures (Kaiatan-Runangan), Ruatangata Sandstone (Runangan), Whangarei Limestone (Landon), and Waitakian sandstones are referred to the Te Kuiti Group. The Onerahi Formation of Ferrar has been re-defined as comprising a chaotic assemblage of upper Cretaceous and Eocene argillaceous rocks, and much rarer Waitakian sandstones, that now overlies the Te Kuiti Group and probably the Parahaki dacites of about Taranaki age. This formation is considered to have been emplaced locally by gravity slumping, shortly after Kaikoura faulting. Its source was probably an overthrust, nappe, piercement, or diapiric structure to the west. Kerikeri basaltic volcanism followed the formation of a terrace at about 220 ft A.S.L. (Milazzian).

Tectonic strikes show a consistent difference of 15° to 20° from those observed at Waihi.

The coal is relatively high in ash, mostly as calcite veinlets, except in those areas of the mine where the limestone cover is thin, or missing. Some coal remains, but it can only be worked if a safe and economic method is developed for mining below flooded workings. The flooding followed pillaring below cavernous limestone, and eventually a rate of inflow was established of about 10 g.p.m. for each foot of hypothetical drawdown below the level of the mine portal. This water was connected to an apparently limitless source of confined groundwater, that was also connected to the local source of carbon-dioxide impregnated "soda-water".

INTRODUCTION

Sub-bituminous coal was mined near Kamo, 4 miles north of Whangarei (Fig. 1), almost continuously from 1876 when Ruatangata Mine commenced serious production, until 1955, when New Kamo No. 3 Mine was flooded (Turner *et al.*, 1957). Ferrar (1925) and Hay (1947a) published geological and historical accounts of the field, and gave adequate reviews of the existing literature. In discussing the age and distribution of coal measures in Northland, Healy (1949) recorded the ages of certain rocks near Whangarei, and Hay (1952) introduced new stratigraphic terms for Northland in general that could be applied to the Kamo area in particular.

Additional geological information has been obtained recently from several sources. In 1953-4 Messrs Brown Bros. of Hamilton drilled 10 holes for the Department of Mines in an attempt to locate extensions to New Kamo No. 3 Mine, and further holes were drilled following the complete flooding of the mines in November 1955. The present

N.Z. J. Geol. Geophys. 2 : 541-68.

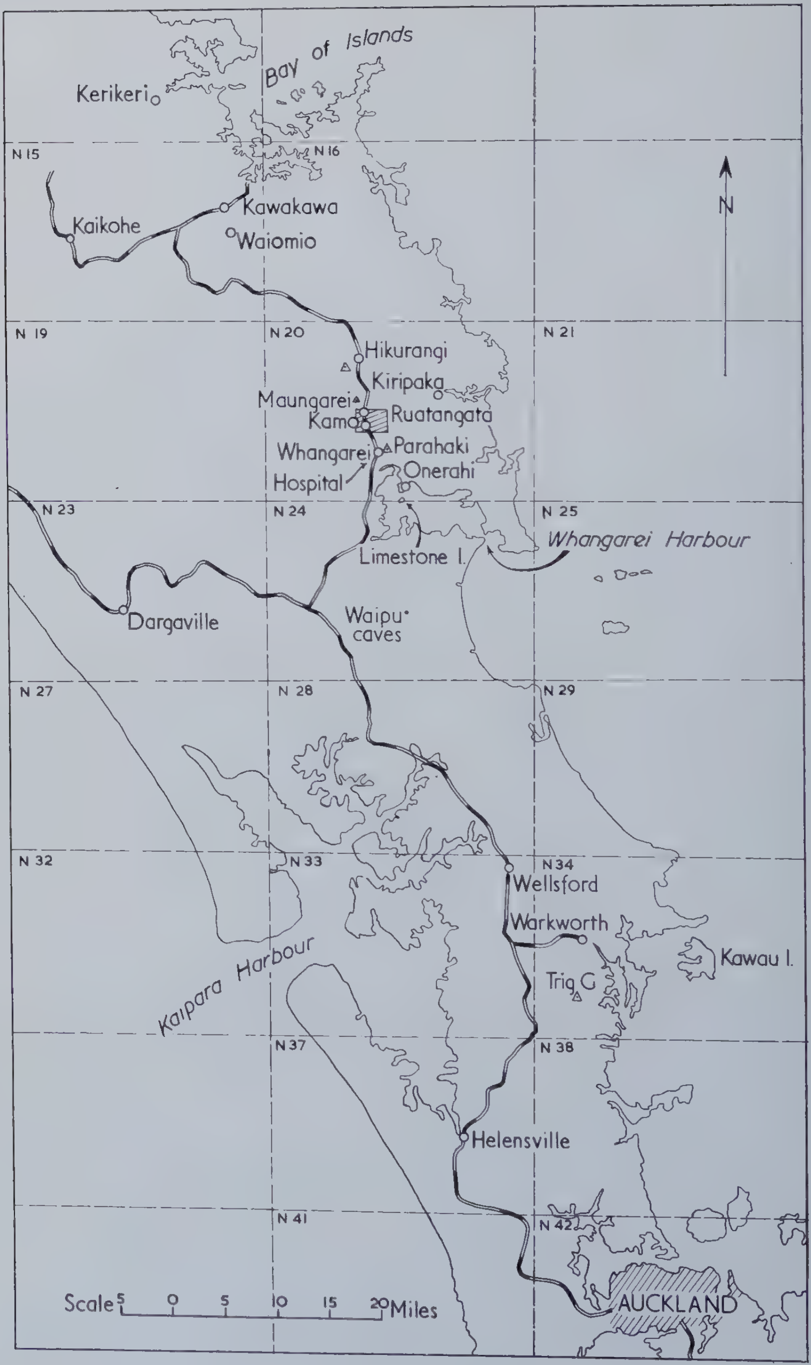


FIG. 1.—Locality Map of part of Northland, showing Kamo Mine Area.

author undertook a detailed coal sampling programme in October 1953 which covered all accessible workings of that mine, and re-examined the few available surface outcrops at Kamo and in other parts of the Northland Coalfield. The drilling data are summarized in Table 1, and were of major importance in the compilation of revised geological maps (with isopachs and structural contours, Figs 2, 3a-3d), geological sections (Fig. 4), and a detailed stratigraphical column (Table 2). The present paper gives particular attention to the stratigraphy and age of the rocks that Ferar (1925) mapped locally as Onerahi Formation, to the stratigraphical positions of the local volcanic rocks, to the regional implications of the structure at Kamo, and to the significant features of the mine flooding.

STRATIGRAPHY

Outline

Table 2 presents a detailed stratigraphic column, and records the more important events of the geologic history of the Kamo area. The detailed descriptions given in this table will not necessarily be repeated in the text, where certain salient points only will be discussed.

Basement

WAIPAPA (Clarke, 1908), AND OTHER GROUPS

At Kiripaka, to the east of Kamo (Fig. 1), Waipapa Group greywackes and argillites are exposed unconformably beneath the coal measures. Similar rocks have been encountered in all drillholes except one (51) beneath the coal measures at Kamo, and crop out south-west of the township. Some cores have shown sedimentary slump structures and dips of 30° to 45° in the greywacke, and many have shown zeolite or quartz veining.

Drillhole 51, after passing through coal measures, finished in 10 ft of greenish-grey indurated mudstone which would be correlated, in general, with Ferrar's (1925) Onerahi Formation. Hay (1947b, p. 316) recorded "Onerahi Series" similarly between "Whangarei" coal measures and Waipapa strata at Kawakawa in his drillhole 3A. It will be shown below, however, that the term "Onerahi" would apply correctly only to rocks of a late Tertiary age. Similar rocks that are stratigraphically below the coal measures and of an upper Cretaceous to Eocene age, require new stratigraphical names. Hay's (1952) introduction of "Mangakahia" and "Opahi" groups will prove invaluable when those terms have been formalized by the descriptions of the constituent formations at their type sections.

Te Kuiti Group

(Kear and Schofield, in press: after Henderson and Ongley, 1923)

TABLE 1.—Drillhole Data for Area of Fig. 2.

Drillhole				Thickness (in feet, to nearest foot, or nearest ½ foot in coal) of Strata Penetrated														
Number on Fig. 2	Old Number	Reference	Datum Height (A.S.L.)	Surface Clay	Kerikeri Basalt	Clay Conglomerate	Onerahi Formation	Waitakian Sandstone	Whangarei Limestone	Ruatangata Sandstone	Green Sandstone	Kamo Coal Measures	Upper Coal	Parting	Lower Coal	Coal Measures	Final Depth (ft)	Remarks
1	1	Hay, 1947	446·0	30	—	—	124	12	129	107	86	—	12	13	11½	1	526	
2	2		319·7	82	—	—	169	103	156	144	72	—	6	39	6½	0	777	
3	3		c370	20	—	—	22	7	80	78	71	—	7	2	11	0	298	
4	4		261·0	12	—	—	102	—	132	71	82	3	11	½	1½	14	430	
5	5		264·3	8	100	—	64	—	51	88	85	—	8½	2½			409	
6	6		c410										1½	5½	7½		149	Overburden 134 ft
7	7		c420	—	182												182	
8	8		c420	—	280												280	
9	9		c380										10				156	Overburden 146 ft
10	10		372·3	31	115	x											330	Soft sst 146-194 ft
11	11		c300	38	17	29	x										84+	
12	12			26	179												205	South of Fig. 2
13	13		c300	5	—	—	195										200	
14			c400	—	—	—	170	—	50	60	70	—	12	60	12		414	Air Shaft
15	1	Ferrar, 1925	c200	28	—	—	—	—	—	210		—	8½				246	
16	2																	South of Fig. 2
17	3																	No data
18	4		c250										x					
19	5																	No data
20	6		c160	28	—	—	—	—	—	—	75	—	5				108	
21	1	Browns Drilling 1953-4	317·2	34	—	39	65	67	151	112	99	43	0	—	—	11	665	To greywacke
22	2		322·9	27	—	49	—	147	152	95	77	1	2½	36	3½	28	636	To greywacke
23	3		287·2	15	72	25	30	68	158	95	82	4½	½	4¾	1	81	693	To greywacke
24	4		290·4	30	89	—	31										150	

25				29	—	—	—	68	283								370	Geological Survey Rig
26	6	Browns Drilling 1953-4	298·7	16	17	43	94										170	
27	7		299·1	18	26	34	542	10	143	99	85	15	8½	—	—	3	1063	To greywacke
28	8		212·0	—	81	22	236	25	77	78	71	—	0	—	—	2½	639	To greywacke
29	9		246·3	—	123	44	—	54	77	90	74	—	2	—	—	19	510	To greywacke
30	10		252·9	—	128	55	—	27	56	92	89	1½	5	2	¼	32	488	
31	11		289·6	—	24	26	520	70	180	90	84	2	½	33	2¼	8	1050	To greywacke
32	X	Ferrar, 1925	c380	?	—	—	—	—	28	210		—	9½				?	
33	Y				x				x									
34	1	Kamo Mine Plan SCM 40	—	—	—	—	—	—	—	—	—	—	x	46	x	—	?	Underground
35	2		—	—	—	—	—	—	—	—	—	—	x	x	x	—	?	Underground
36	3		—	—	—	—	—	—	—	—	—	—	x	44	x	—	?	Underground
37	—												10					On old mine plan
50	50	Browns Drilling 1956	330·8	7	—	—	3	—	—	21	63	0	4¼	36	3½	52	220	To greywacke
51	51		329·0	5	—	—	6	—	—	30	38	12	1	42	1¾	48	195	To argillaceous basement
52	52		331·2	4	—	—	34	—	—	23	30	—	¼	59	1	56	220	To greywacke
53	53		331·0	16	—	—	27	—	43	28	26	10	1½	26	¼	6	191	To greywacke
54	54		388·5	12	6	—	62	—	—	62	46	21	1½	31	½	53	300	To greywacke
55	55		445·5	6	—	—	44	—	52	178	71	0	¼	31	½	48	435	To greywacke
56	56		415·0	15	—	—	46	—	79	213	63	84	¼	48	¼	28	585	To greywacke
57	57		371·4	16	—	—	40	—	76	110	74	—	—	36	—	—	360	To greywacke
58	58		424·5	12	—	—	54	—	135	70	93	—	6½	11	25	45	500	To greywacke
59	59		363·7	18	—	—	70	—	68	62	76	—	8¾	20	¼	19	365	
69	69		453·4	7½	—	—	132	—	138	144	74	6	0	18	0	20	550	To greywacke
70	70		465·9	12	—	—	162	—	95	113	66	—	1½	1½	6	58	525	To greywacke
100	100		371·8	9	139	—	—	—	—	8	68	20	20				235	Into mine drive
101	101		317·5	—	84	41	18	—	2½	85	93	—	11½	36	—	—	380	To greywacke
102	102		326·7	—	96	12	—	—	29	102	97	—	16	½	1½	35	410	To greywacke
103	103		316·0	—	97	26	—	—	28	98	99	—	14	47	—	—	440	To greywacke
104	104		277·2	10	107	11	—	—	8	93	83	—	11	12	—	—	350	To greywacke
105	105		280·3	—	152	26	—	—	17	87	74	—	½	10	6¾	27	420	To greywacke
106	106		257·0	20	106	18	16	—	—	109	50	7	5½	47	—	—	420	To greywacke. Coal dirty
107	107		308·8	—	34	26	—	—	8	45	70	—	26½	2½	6½	26	300	To greywacke
108	108		250·0	—	195	5	—	—	28	72	94	—	1½	36	—	—	450	To greywacke
109	109		373·4	12	144	1	—	—	—	—	—	—	—	—	—	—	210	To greywacke
110	110		260·4	12	97												109	

TABLE 2.—Stratigraphic Sequence in Kamo Mine Area.

Age	Formations with Lithologies	Approximate average thickness where full sequence present (ft)	Normal total range in thickness (ft)
Holocene	Alluvium, etc. White and blue clays, alluvial sands, swamp	20	0-280
Upper Pleistocene	KERIKERI BASALT Basaltic flows, scoria and tuff	100	0-280
	Clay and Gravel: Blue (less commonly yellow white) clays, rarely carbonaceous: rarer sands: and greywacke gravels (pebbles to ½ inch) especially near base	30	0-55
	Formation of 220 ft (Milazzian) Terrace		
Lower Wanganui to Taranaki	ONERAHI FORMATION Chaos of Eocene, Cretaceous, and rarely Waitakian mudstones (grey, greenish or chocolate-brown), sandstones, and "argillaceous limestones. The thickest "beds" are of grey calcareous mudstone (up to 250 ft) and limestone (up to 100 ft)	110	0-542
	Kaikoura Orogeny		
	PARAHAKI AND WAIRAKAU VOLCANICS	Not Drilled	
? Pareora to Waitakian	"Waitakian" sandstones Calcareous sandstone with mudstone beds	50	Up to 54
	Calcareous grey (less commonly yellow, brown or green) sandstone with rare shells	60	57-93
	Rubbly limestone conglomerate	5	0-15

		Erosional Break		
? Waitakian to Whaingaroan	TE KUITI GROUP	WHANGAREI LIMESTONE		
		Thin bedded, grey impure limestone (is present with only 140 ft or more of crystalline limestone below)	5	0-18
		White (less often pink) crystalline limestone; cavities, fractures and broken rock throughout) basal greesand	140	41-283
Runangan		RUATANGATA SANDSTONE		
		Calcareous grey sandstone, with mudstone beds near top: upper 10-50 ft may be glauconitic (even greensand) and pebbly cavities locally	100	62-213
		Glauconitic sandstone, with shells and some mudstone (55-75 ft) .... Purplish or brownish-grey sandstone with yellow efflorescence, and locally basal shell-bed and conglomerate (0-20 ft)	75	26-99
Runangan to Kaiatan	↓	KAMO COAL MEASURES Sandstone (normally 0 ft, range 0-15 ft) Upper Coal Seam (0-26 ft) .... Parting (carbonaceous mudstone, sandstone, fireclay, thin coal, rarely shells) (0-60 ft) .... Lower Coal Seam (normally 0-4 ft) rarely 25 ft) Fireclay with basal sandstone and rarely conglomerate (normally about 20-30 ft, range 0-80 ft)	65	21-160
		Regional Unconformity		
? Lower Tertiary to ? Upper Paleozoic		BASEMENT "Mangakahia" or "Opahi" Groups Eocene and Cretaceous mudstones, limestones, rare sandstones.		
		WAIPAPA GROUP Non-Calcareous grey greywacke and argillite; with calcite and rare quartz stringers.		

INTRODUCTION

Ferrar (1925, pp. 34-49) extended the application of the stratigraphical term "Whangarei" from a limestone formation (Cox, 1881, pp. 17-19) to a number of rock units that would now be collectively styled a "group". He used the name Whangarei "Formation", however, and included therein (p. 44):

(f) Calcareous grit
(e) Calcareous mudstone or fine sandstone
(d) Whangarei or crystalline limestone
(c) Argillaceous or glauconitic sandstone
(b) Quartz grits with coal
(a) Conglomerates

The two upper units are substantially different in age from the rest, for Ferrar considered that the topmost grit (f) represented a "sea-beach as the land continued to rise towards the close of the Tertiary" (p. 46), and formation (e) is considered to be Taranaki to lower Wanganui in age (i.e. part of the redefined Onerahi Formation, see below). The remaining formations, with the possible addition of a Waitakian sandstone, which immediately overlies the Whangarei Limestone, form a useful group of strata, however, and should be styled as a group.

Preferably, geographical names that are used for groups should differ from those used for formations, and thus it would be desirable to restrict the application of "Whangarei" to the limestone formation as originally intended. The formations of the group under discussion constitute a transgressional sequence from Arnold coal measures through normal shelf marine beds to a Landon crystalline limestone. They thus resemble strikingly the constituent formations of the Te Kuiti Group (Kear and Schofield, in press) and not withstanding the distance between Kamo and Te Kuiti, it is proposed that the term "Te Kuiti Group" apply to them as well. The oldest marine beds are slightly older at Kamo (Runangan) than they are at Huntly or Te Kuiti (Whaingaroan). A difference of the same apparent magnitude, however, exists 20 miles south-east of Te Kuiti at Mangapehi, where the oldest marine beds are Duntroonian (Gage 1942). This fact is not generally considered to be any barrier to the use of the term "Te Kuiti" at Mangapehi.

The constituent formations of the Te Kuiti Group at Kamo are: Kamo Coal Measures (base), Ruatangata Sandstone, and Whangarei Limestone, with the tentative addition of Waitakian sandstones at the top. The latter sandstones have not been examined in outcrop, and therefore their formational naming is left to the future. An erosional break below them may demand separate grouping for them.

KAMO COAL MEASURES

Kamo township is 4 miles north of Whangarei. The type locality for the Kamo Coal Measures is immediately south of Ruatangata railway station (Fig. 2) at the northern boundary of the township,

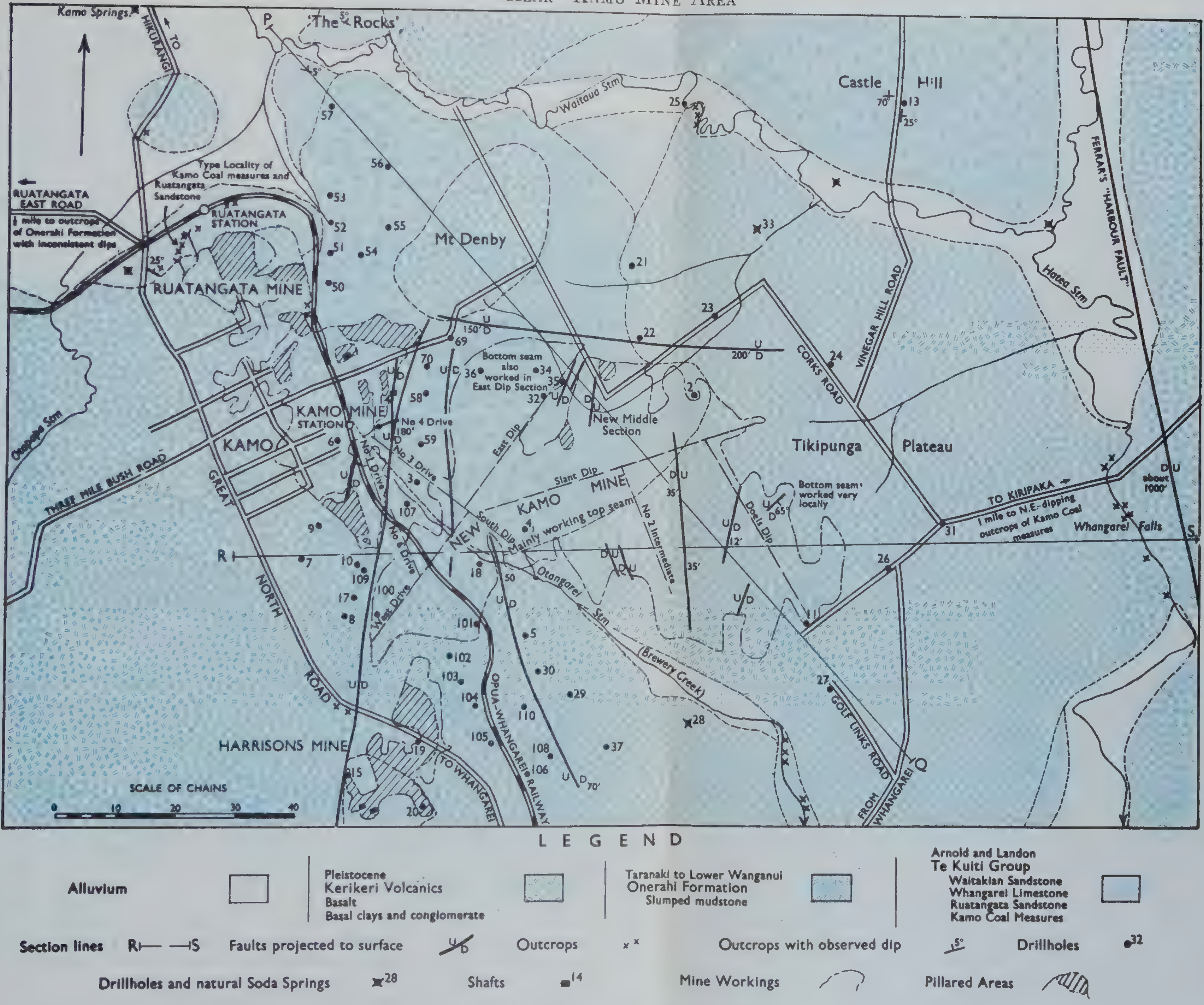
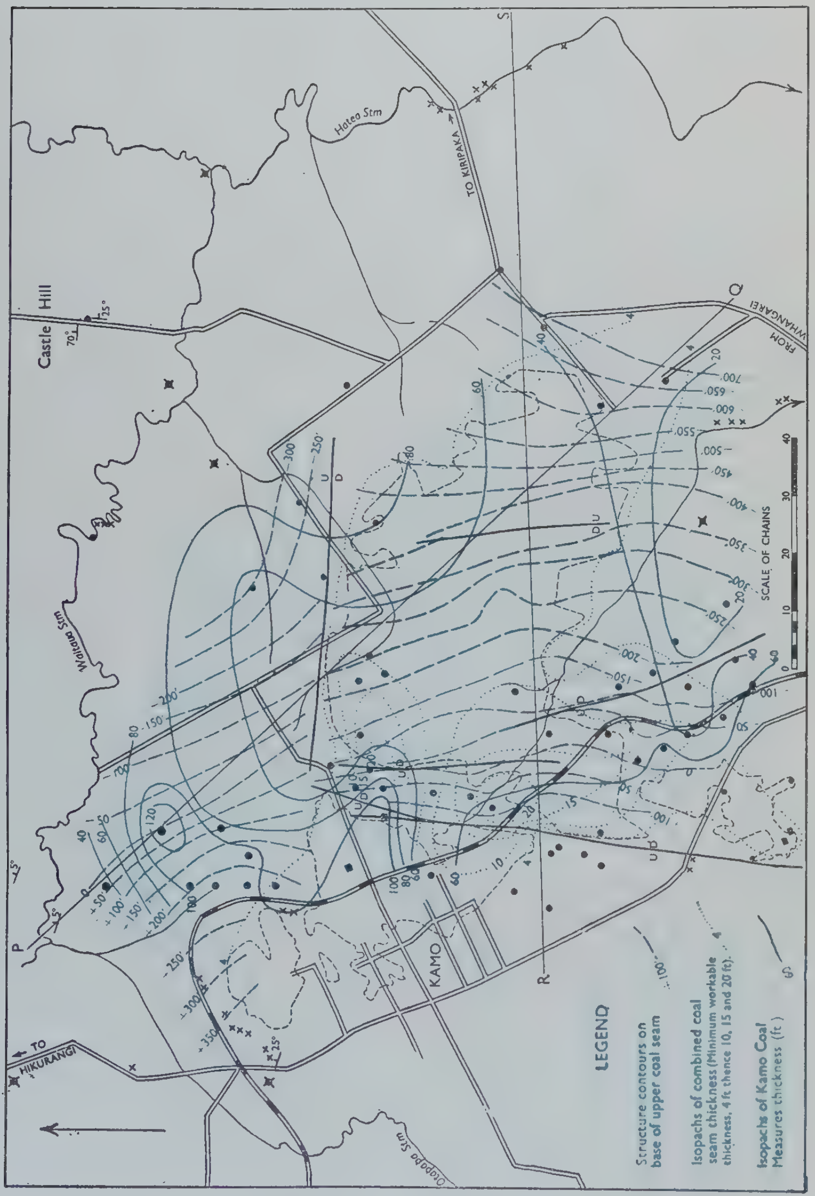
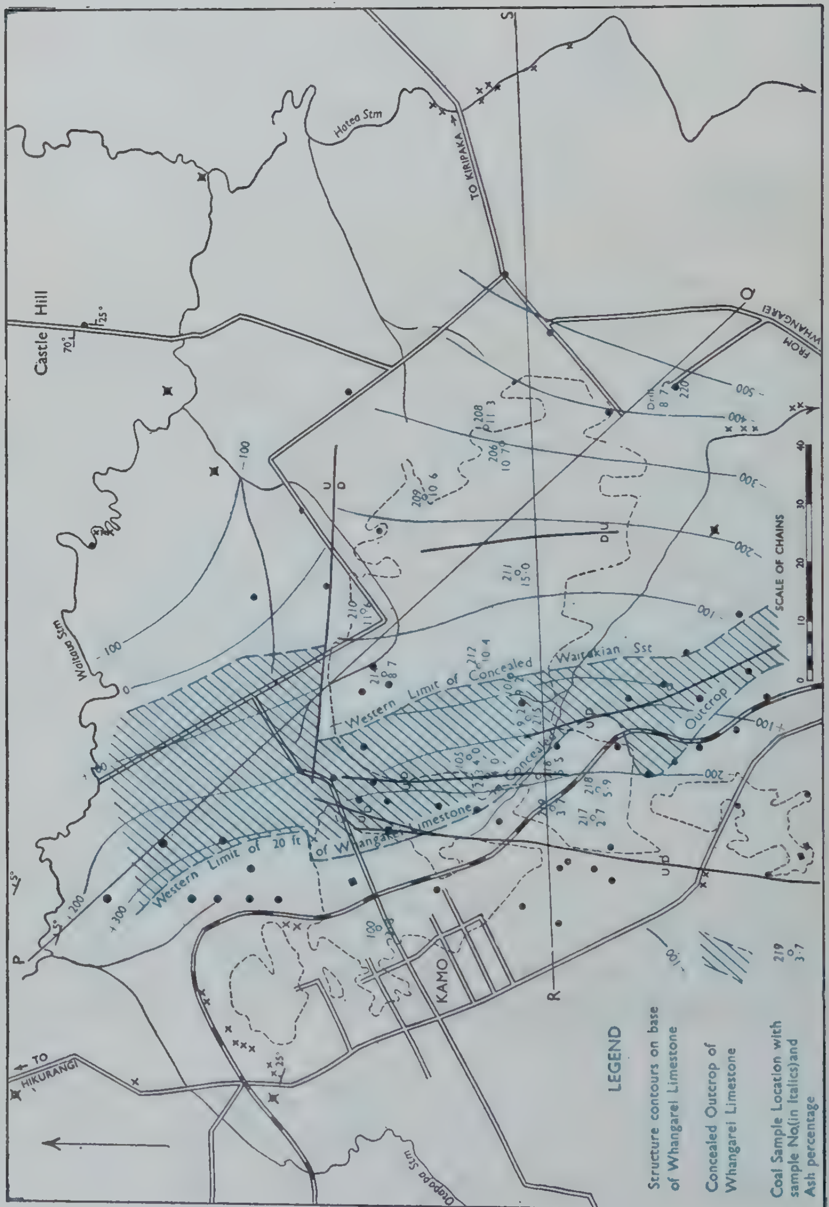


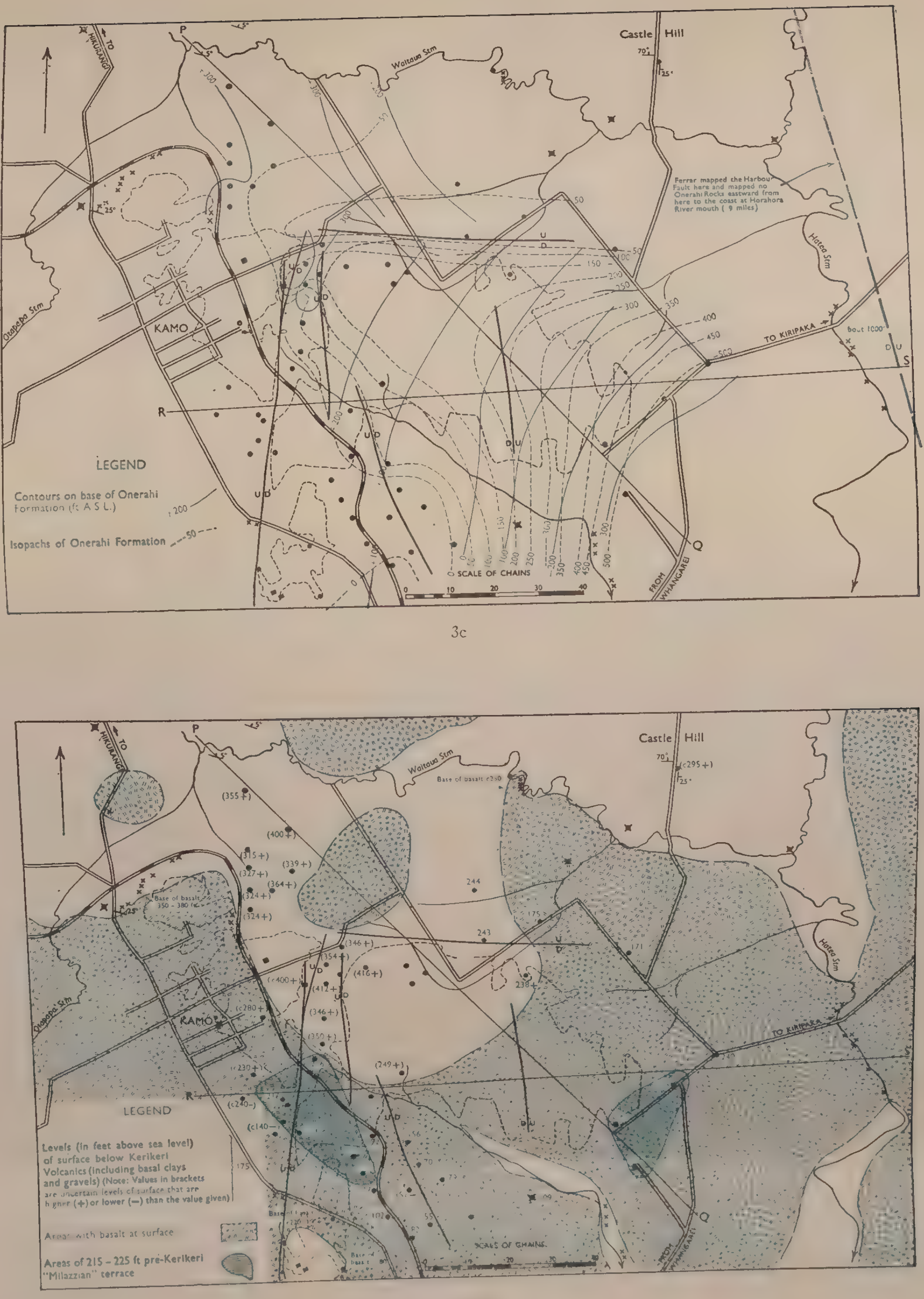
FIG. 2.—Geology of Kamo Mine Area.


LEGEND
Structure contours on base of upper coal seam
Isopachs of combined coal seam thickness (Minimum workable thickness, 4 ft thence 10, 15 and 20 ft).
Isopachs of Kamo Coal Measures thickness (ft)
SCALE OF CHAINS
Castle Hill
Waitaua Stm
Hatea Stm
TO KIRIPAKA
FROM WHANGAREI
TO HIKURANGI
KAMO
Otapapa Stm
P
Q
R
S

3a


LEGEND
Structure contours on base of Whangarei Limestone
Concealed Outcrop of Whangarei Limestone
Coal Sample Location with sample No. (in italics) and Ash percentage
Western Limit of Concealed Waitakian Sst Outcrop
Western Limit of 20 ft of Whangarei Limestone
Concealed
SCALE OF CHAINS
Castle Hill
Waitaua Stm
Hatea Stm
TO KIRIPAKA
FROM WHANGAREI
TO HIKURANGI
KAMO
Otapapa Stm
P
Q
R
S

3b


Castle Hill
Waitaua Stm
Hatea Stm
Otaipapa Stm
KAMO
TO HIKURANGI
TO KIRIPAKA
FROM WHANGAREI
P
Q
R
S
U
D
Ferrar mapped the Harbour Fault here and mapped no Onerahi Rocks eastward from here to the coast at Horahora River mouth (9 miles)
Bout 1000'
SCALE OF CHAINS
0
10
20
30
40
LEGEND
Contours on base of Onerahi Formation (ft A.S.L.)
Isopachs of Onerahi Formation
Base of basalt c250
Base of basalt 350 - 380 ft
Levels (in feet above sea level) of surface below Kerikeri Volcanics (including basal clays and gravels) (Note: Values in brackets are uncertain levels of surface that are higher (+) or lower (—) than the value given)
Areas with basalt at surface
Areas of 215 - 225 ft pre-Kerikeri "Milazzian" terrace

3c

3d

FIG. 3.—Detailed geology of the several formations of the Kamo Mine area. Fig. 3a shows structure contours on the floor of the upper seam, and isopachs for the coal measures and for the combined workable thicknesses of the two seams; Fig. 3b shows structure contours on base of Whangarei Limetone, the concealed outcrop of that formation, and the localities (shown by sample numbers within sheet N20) and ash contents of coal samples; Fig. 3c shows isopachs for the thickness of Onerahi Formation penetrtaed in Kamo drillholes, and structure contours on the base of that formation; and Fig. 3d shows reduced levels of the base of the Kerikeri Volcanics (including basal clays and conglomerates within that formation), and areas of the "Milazzian" terrace (about 220 ft A.S.L.).

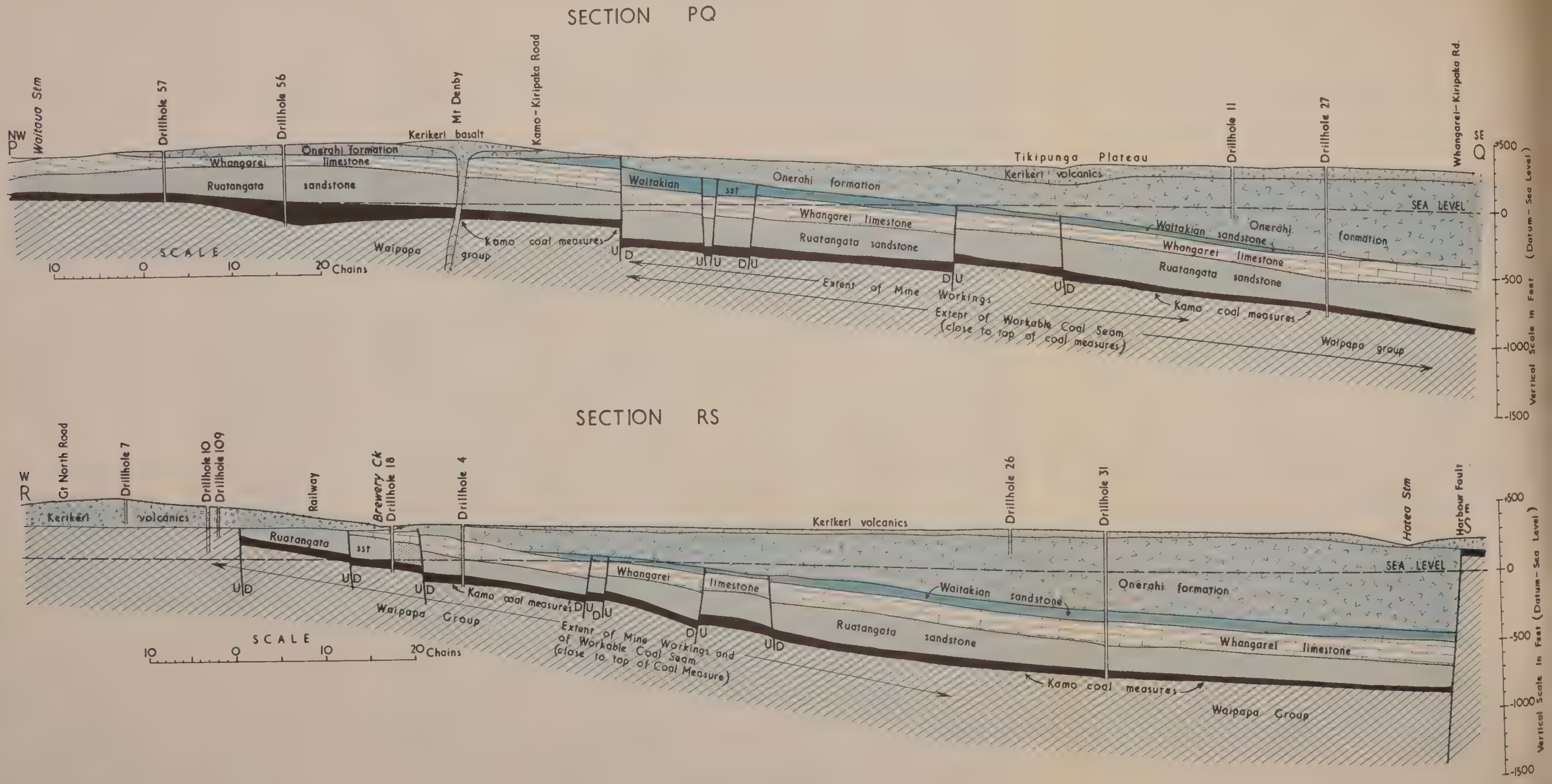


Fig. 4.—Geologic Sections for the Kamo Mine Area.

where the following beds are exposed below red-brown basaltic clays in the brickworks pit:

		(ft)
Type Section of Ruatangata Sandstone	Weathered light brown glauconitic shaly sandstone, with flattened mollusc casts	6
	Brown-grey glauconitic sandstone with yellow efflorescence: greenish, and with mollusc casts at top; carbonaceous and purplish towards base, with coaly fragments, and with greywacke and quartz pebbles in 6 inch conglomerate beds	20

Type Section of Kamo Coal Measures	Coal	2
	Carbonaceous sandstone	2
	Carbonaceous mudstone, sandy towards base	10
	Interbedded coal and carbonaceous mudstone, mixed with clayey debris; representing collapsed old mine workings	3

Two coal seams are commonly present within the measures, and both have been worked in several mines. In New Kamo No. 3 Mine, as generally elsewhere, the upper seam was worked in preference to the lower, since it was usually the thicker. A parting, up to 60 ft thick, separates the seams, but it thins markedly to the south-east where the two seams almost run together. The coal itself will be discussed separately in a later section.

Figure 3a shows structure contours on the floor of the upper seam, and isopachs for the coal measures and for the combined workable thicknesses of the two seams. Correlations noted in other fields between thick coal and thick measures is by no means well demonstrated at Kamo.

Shells were recorded within "fireclay" in drillholes 51 and 52 ($33\frac{1}{2}$ to $39\frac{1}{2}$ ft and $10\frac{1}{4}$ to $26\frac{1}{4}$ ft respectively below the top of the coal measures). These, together with carbonaceous material in the lower part of the overlying Ruatangata Sandstone, suggest that no significant break occurs at the top of the coal measures. The latter will thus be immediately older than the Ruatangata Sandstone of Runangan age, and are probably Kaiatan-Runangan (see also Healy, 1949, p. 286).

RUATANGATA SANDSTONE

Ruatangata is the name applied to the northern part of Kamo township, and is the type locality for the Ruatangata Sandstone (see description above, under "Kamo Coal Measures"). Healy (1949, p. 285) recorded the collection of three greensand samples from Ruatangata which contained Runangan Foraminifera. The formation comprises Ferrar's bed (c) (Ferrar, 1925, p. 44), and Hay's sandstone and glauconitic sandstone (Hay, 1946, geological sections). Its basal fossiliferous beds commonly rest directly on the coal (e.g. McKay, 1884, p. 119), and fossiliferous sandstone with marine borings usually formed the roofs of the mine workings.

The Ruatangata Sandstone is much better known from drillholes than from outcrops. The following sequence was measured in New Kamo Mine No. 3 Drive:

	(ft)
RUATANGATA SANDSTONE:	
Grey calcareous silty sandstone (Foraminiferal Samples N20/606 (F. 10108), 75 ft up; N20/607 (F. 10109), 30 ft up	100
Grey moderately calcareous glauconitic fine sandstone (Samples N20/608 and 609 at top and base showed no Foraminifera)	70
Purplish-grey carbonaceous sandstone with yellow efflorescence	10
Grey shelly fine sandstone with carbonaceous fragments	5
Fine Conglomerate	2
KAMO COAL MEASURES:	
Sandstone with carbonaceous streaks	15
Upper Coal Seam.	

Mr N. de B. Hornibrook (pers. comm.) considered the above samples N20/606-7, and others from 180 ft and 60 ft above the coal in drillhole 27 (respectively N20/604 and 603 F. 10106-7), to be of Runangan age. Dr H. J. Finlay gave age determinations (*in* Healy, 1949, p. 285) of Runangan for three samples from Ruatangata (including one immediately below the Whangarei limestone), and of Whaingaroan and Runangan for samples immediately and 100 ft respectively below the limestone at Whangarei Hospital. The former could well be considered to be basal Whangarei Limestone formation, and the Ruatangata Sandstone may therefore be considered tentatively as Runangan throughout.

Ferrar (1925, p. 112-3) recorded data from 18 drillholes at Hikurangi (6 miles north of Kamo) that penetrated both crystalline limestone and coal measures. These, together with two holes drilled in 1956, showed an average of less than 20 ft of sandstone (which might have been Kamo Coal Measures in part) between the limestone and the top coal seam. Thus the Ruatangata Sandstone, which averages 200 ft at Kamo, thins considerably northwards. At Waiomio, 15 miles northwest of Hikurangi, the 2 ft of conglomerate that was penetrated by hole 3A (Hay, 1947b, p. 316) would be the sole possible representative of the Ruatangata Sandstone.

The Ruatangata Sandstone is sufficiently calcareous to contain solution cavities, as low as 115 ft above workable coal in drillhole 101, and 65 ft above thin coal in drillhole 50.

WHANGAREI LIMESTONE (Cox, 1881, pp. 17-19)

Figure 3b shows structure contours of the base of the Whangarei Limestone (as indicated by drillholes), and also the concealed outcrop of that formation beneath Quaternary rocks. The presence of thin limestones in the upper part of the Ruatangata Sandstone made it necessary to define the lower Whangarei Limestone contact by the presence of at least 20 ft of limestone in drill-logs.

The Whangarei Limestone is probably of Landon age, as are the other thick crystalline limestones of the Te Kuiti Group.

SANDSTONES OF WAITAKIAN AGE

Sandstones that overlie the Whangarei Limestone are of Waitakian age (Mr N. de B. Hornibrook's determinations, in pers. comm., of samples N20/597 and 598 (F. 8724, and 8931) collected from 51 ft and 63½ ft respectively above the limestone in drillhole 23). A conglomerate at their base suggests an erosional contact between them and the limestone, and this is consistent with the fact that the thin sandy limestone bed at the top of the Whangarei Limestone is present only where 140 ft or more of the formation is present, and that the thickness of Whangarei Limestone below the Waitakian sandstones ranges from 80 ft to 180 ft within the eastern part of the Kamo area. This break may be equivalent to the post-Te Kuiti erosion break elsewhere, but the Waitakian sandstones of Kamo will be included in that group at least until they have been inspected thoroughly in surface outcrops.

Waitakian or lower Pareora microfossils (Mr N. de B. Hornibrook, pers comm.) have been obtained from samples of calcareous sandstone (N24/562, F. 10110) immeditaely above the Whangarei Limestone at Waipu Caves, 20 miles south of Kamo (Fig. 1).

Parahaki and Wairakau Volcanics

(Ferrar, 1925; Bell and Clarke, 1909)

Ferrar (1925, pp. 59-61, 66-7) referred the eroded volcanic cones of Parahaki and Maungarei (Fig. 1) to the Parahaki "Series", and that of Hikurangi (Fig. 1) to the Wairakau "Series". He was by no means certain of the latter two identifications; but his placings will be accepted here, with the observation that Hikurangi's preservation suggests an age approximately intermediate between the Wairakau and Parahaki volcanics. The Wairakau volcanics are considered to be correlatives of the Beesons Island Volcanics of Taranaki to lower Wanganui age, and the Parahaki volcanics to be a product of late Beesons Island volcanism, or to be slightly younger (Kear, 1957, pp. 678-9).

Maungarei volcanic cone lies just outside the area of the present geological map, but the Wairakau and Parahaki volcanics have been included in the stratigraphical column. Both are considered to be younger than the Waitakian sandstones, on the evidence of cone preservation and of correlation with the Beesons Island Volcanics. The Wairakau Volcanics are shown below to be older than the Onerahi Formation at Hikurangi; and the presumed closeness of age of the Wairakau and Parahaki volcanics leads to the tentative proposition that the latter are also older than the Onerahi Formation, although no direct evidence is yet available on this point.

Onerahi Formation (after Ferrar, 1920)

PREVIOUS USAGE

McKay (1884, 1888) maintained that the "hydraulic" limestone of Limestone Island in Whangarei Harbour was younger than the

Whangarei Limestone. Ferrar (1925) placed the hydraulic limestone and associated argillaceous strata in his Onerahi Formation, with a type locality (Ferrar, 1920, p. 5) at Onerahi Peninsula (Fig. 1) where calcareous grey mudstones, with calcite veining, are exposed below a covering of basalt. The Onerahi Formation was more indurated, more sheared, more jointed, and of more complicated structure than Ferrar's "Whangarei Formation". It also resembled upper Cretaceous to lower Eocene rocks elsewhere in New Zealand, and contained fossils of those ages. Ferrar therefore assumed that his Onerahi Formation occupied a stratigraphic position between the Waipapa Group and the Whangarei Formation. His maps of the coalfield area conformed to this theory.

Lithology and Paleontology

Light green-grey calcareous mudstone in Brewery Creek (sample N20/588, F. 8723) contains lower Dannevirke Foraminifera (Mr N. de B. Hornibrook, pers comm.). Weathered brown mudstone, with rare thin quartzose sandstone beds, dips east at 25° (Fig. 2), and north at 70° (Ferrar, 1925) at Castle Hill. Well-bedded, sheared, weathered, greenish or brownish mudstones are exposed on the Ruatangata East Road, ½ mile west of Ruatangata railway station, where they dip chaotically.

Most Onerahi rocks penetrated in drillholes were calcareous grey, green-grey, or chocolate mudstones, although over 100 ft of argillaceous limestone was penetrated by drillhole 27. The drillers' log for that hole, together with Mr Hornibrook's age determinations (pers. comm.) of microfossil samples, are shown below.

	(ft)	Stage
Surface Clay	0-18	
Kerikeri Basalt: Basaltic rocks, with basal sandstone and gravels	18-78	
Onerahi Formation:		
Soft Limestone (muddy nature)	78-89	
Firm Limestone with occasional bands (cuttings Samples N20/592, 125 ft to 160 ft; and 601, 112½ ft to 117 ft)	89-206	Bortonian
Chococlate and grey mudstone, heaving badly (cuttings sample N20/593, 206 ft to 258 ft)	206-258	Bortonian
Light green-grey calcareous mudstone (cuttings sample N20/594 at 360 ft)	258-490	Bortonian
As above, but with hard bands about 6 in. to 2 ft thick, about every 3 ft or 4 ft (sample N20/595 was of fine sandstone collected with cuttings, 586 ft to 620 ft)	490-620	Waitakian
Hard and broken fine sandstone (core sample N20/602, 625 ft to 630 ft)	620-630	Probably Bortonian
Te Kuiti Group:		
Whangarei Limestone	630-773	
Ruatangata Sandstone (core samples N20/603, 787 ft to 800 ft; 604, 890 ft to 920 ft	773-957	Runangan
Kamo Coal Measures	957-984	
Waipapa Group: Greywacke	984-1063	

Dr H. J. Finlay (*in* Healy, 1949, p. 285) determined the age of calcareous mudstones, ½ mile south of Whangarei hospital, as Teurian.

RELATION TO OTHER FORMATIONS

Strata that Ferrar would presumably have mapped as Onerahi, and which are in the stratigraphic position that is indicated by their upper Cretaceous to lower Tertiary fossils, have rarely been located in drillholes beneath the Kamo Coal Measures. They should be designated by stratigraphic names other than "Onerahi" (see "Basement" above).

The bulk of Ferrar's Onerahi Formation within the immediate areas of the Northland Coalfields, however, occupies a stratigraphic position above the Te Kuiti Group. A few widely scattered examples of this relationship will suffice. At Kawakawa, Healy (1945, p. 234) recorded Onerahi strata overlying Whangarei Limestone in drillholes. At Waiomio, south of Kawakawa, Ferrar mapped an area of "grey marl", centrally on top of a large exposure of Whangarei Limestone, which is in fact chocolate and light grey mudstone—typical of his Onerahi Formation elsewhere. At Hikurangi Ferrar (1925, p. 113) ignored or discredited two drillholes (1A and 2) that reported coal after commencing in Onerahi Formation; but coal was later mined below both drillholes by Wilsons and Waro Mines. At Kamo, in drillhole 27 (see above), 542 ft of Bortonian Onerahi mudstones and limestone overlie Runangan and younger Te Kuiti rocks; and the Onerahi mudstones of Castle Hill (Fig. 1) were previously suspected by Healy (1949, p. 285) of being younger than the Whangarei Limestone. At Abbey Rocks, 4 miles south-east of Kamo, the Whangarei Limestone appears to dip beneath grey and chocolate weathered mudstones. At Whangarei, a mile east of the limestone outcrop at the hospital, Te Kuiti sandstones are exposed along the Great North Road, and form the base of a hill which is capped by blocky jointed siltstones that Ferrar mapped, quite reasonably, as Onerahi Formation.

Thus, many if not most of the Onerahi rocks around the Northland Coalfields occupy post-Te Kuiti stratigraphic positions. At Onerahi Peninsula itself the relationship has not yet been established in drillholes. However, the nearest contacts to the north (Abbey Rocks) and west (Whangarei, 1 mile east of hospital) show Onerahi rocks overlying Te Kuiti. McKay (1884, 1888) considered the Onerahi of nearby Limestone Island to be younger than the Whangarei, and Ferrar mapped no Onerahi Formation to the east between the small areas of Whangarei "Formation" and the underlying Waipapa rocks. It is thus assumed that the type Onerahi rocks also occupy a post- Te Kuiti stratigraphic position, and that the term "Onerahi" should be restricted to such rocks. It should not be used to designate similar argillaceous limestones and mudstones that are in the upper Cretaceous to Eocene stratigraphic position that is consistent with their contained fossils.

The Onerahi Formation (in the above sense) is also exposed in cuttings towards the top of a steep hill on the Great North Road, 6 miles south of Warkworth and a mile south-east of Trig G (Fig. 1). It fills erosional depressions in the Waitemata Formation, which was considered to be of Southland age by Finlay and Marwick (1948, p. 24).

Onerahi claystones overlie the lower flanks of Hikurangi Mountain (see, for example, Ferrar's detailed geologic map of the Hikurangi Coalfield, 1925), and are thus post-Wairakau Volcanics in age. They are also presumed to be post-Parahaki (see above). Drillholes in the Kamo mine area show that the basalts there locally overlie the Onerahi rocks. Thus, the latter are in a post-Parahaki and pre-Kerikeri stratigraphic position.

TIME OF EMPLACEMENT

Clearly the great bulk of the coalfield's Onerahi rocks are not now found in the stratigraphic position that would be assigned them on the grounds of lithology and paleontology. Their age appears to be younger than the Parahaki Volcanics (probably Taranaki at oldest) and older than the Kerikeri Volcanics of Pleistocene age (see below). Their extreme age range would therefore be upper Miocene to Pleistocene. It is probably no coincidence that this time range included the maximum activity of the Kaikoura Orogeny which was responsible for the faulting and tilting of the Te Kuiti Group.

Figure 3c shows the thickness of Onerahi Formation penetrated in Kamo drillholes. Unfortunately the drillhole spacing was too wide to allow isopachs to be constructed accurately. However, every solution shows a tendency towards thickening on the downthrown sides of faults, and the isopachs that are shown were drawn to emphasise that point. The very great thickening (to over 500 ft) towards Ferrar's (1925, Whangarei S.D.) Harbour Fault (Fig. 3c) is particularly noticeable. No Onerahi rocks were mapped by Ferrar in the 9 miles of hilly country from this coal-measure outcrop to the east coast.

The facts that considerable increases in thickness of the Onerahi Formation occur across several Tertiary faults, that these increases are numerically at least half as much as the throws on the respective faults, and that the 500 ft of Onerahi rocks to the south-east of Kamo are unweathered, all suggest, firstly that the Onerahi beds were emplaced relatively soon after the faulting took place, and secondly that the Kaikoura Orogeny was responsible, at least indirectly, for their emplacement. The age of the Kaikoura Orogeny in Northland is uncertain, but is probably very similar to its age in south-west Auckland where it pre-dates the Kaawa Formation, and may be Taranakian (Marwick, 1948, p. 17).

Thus, the Onerahi rocks of Kamo Coalfield area are presumed to have been emplaced at some time within the range Taranaki (oldest age for Beesons Island Volcanism) to lowest Wanganui (age of Kaawa beds and thus post-Kaikoura).

MEANS OF EMPLACEMENT

The 500 ft of unweathered Onerahi rocks in the south-eastern part of the Kamo mine area weigh heavily against any suggestion that they accumulated by a process of slow erosion and deposition, and considerable tectonic movements must be postulated. The only debatable point is whether the rocks were emplaced directly by tectonic activity or whether they were merely raised to a considerable height and reached their present positions by gravity slumping.

The available evidence leads to the latter conclusion. Firstly, Ferrar's recorded dips near Kamo (1925, maps) are chaotic both as regards dip direction and dip angle, even where they are closely spaced. The few additional dips measured recently emphasised his findings. Secondly, the present lack of Onerahi rocks to the east of Harbour Fault (opposite Kamo), could imply that they were always thin or absent there. This in turn would imply that the present thickness of Onerahi rocks in the Kamo area is of the same order as the original thickness. It would seem most unlikely that a few hundred feet, only, of argillaceous rocks could remain sufficiently competent during violent thrusting to be recognizable now as a tectonic unit. Thirdly, the Waitakian Foraminiferal fauna above the lowest Bortonian drill cores in drillhole 27 (see Lithology and Paleontology, above) shows that the "Onerahi" includes other rocks besides the predominant upper Cretaceous and Eocene ones. Thus, they are considered to be a chaotic deposit of large blocks that reached their present positions by slumping under gravity from an overthrust, nappe, piercement, or diapiric structure (cf. Fleming, 1947, pp. 114-5) that was presumably located to the west. Somewhere in that direction it may be possible to map complex structures that are unslumped; but at Kamo in particular, and most of the Northern Coalfields in general, the deposit is considered to be no more than a collection of disorientated blocks of various formations that bear little more relationship, one to the other, than do the pebbles of a conglomerate to their immediate neighbours.

The Kerikeri Basalt has covered most of the Onerahi Formation near Kamo, and the surface of the latter is therefore not now available for detailed inspection.

APPLICATION OF NAME AND AGE

Hay's (1947b) implied rejection of "Onerahi" as a formational name for upper Cretaceous and Eocene rocks is strongly supported. New names should be used for those rocks where they appear in their correct stratigraphic position, or where they can be shown to be part of a recognizable tectonic unit (e.g. overthrust sheet) in which identifiable formations appear in explicable relationships to one another. Elsewhere, where these rocks are not demonstrably in their correct stratigraphic positions and where their tectonic relationship to one another is uncertain, it will be possible to map them only as "Onerahi Formation". Such areas will include gravity-slumps, and, if the source were a diapir or piercement structure, will probably comprise the entire deposit.

Thus, the application of the name "Onerahi" has been changed. Ferrar (1925) applied it to upper Cretaceous and Eocene rocks that he thought were in their correct stratigraphic position, whereas it is now suggested that the name apply only to those rocks with upper Cretaceous, Eocene, and rarely Waitakian fossils, that were emplaced stratigraphically above the Te Kuiti Group in Taranaki to lower Wanganui times. Thus, the Onerahi Formation must now be considered to be of Taranaki to lower Wanganui age.

Kerikeri Volcanics (Bell and Clarke, 1909)

Many drillholes show thick basalt, scoria, or tuff overlying thin clays and gravels of presumed Pleistocene age. All are referred here to the Kerikeri Volcanics. Figure 3d gives reduced levels for the drilled base of these clays and gravels (or for the basalt where they are absent). Although the total range of levels is from 55 ft to 244 ft, more than 40% are within the range of 216 ft to 226 ft above sea-level (Fig. 5).

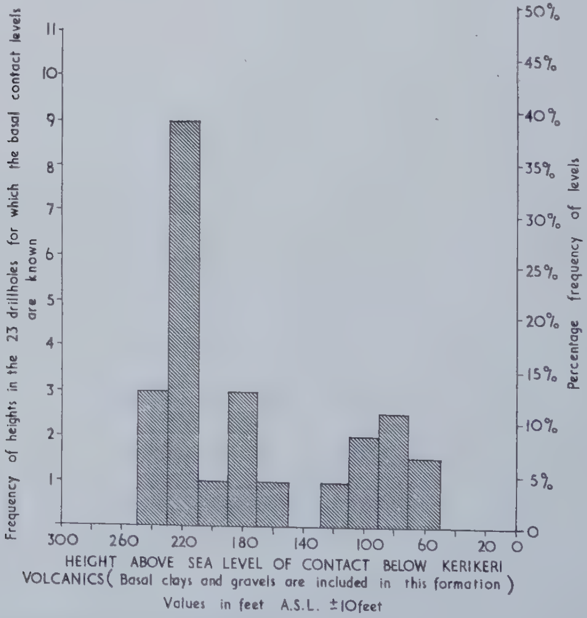


FIG. 5.—The frequency of occurrence of reduced levels (in groups of 20 ft) of the base of the Kerikeri Volcanics, as penetrated in drillholes.

This crowding suggests that the basaltic rocks and their underlying sediments were deposited on a terrace level that may well be a correlative of the Milazzian sea-level terraces (220 to 240 ft) recorded by Brothers (1954, pp. 690-1) from Kaipara Harbour. The Kerikeri Volcanics at Kamo are very probably post-Milazzian. They are also younger than the Kaikoura faulting, since they overlie the Onerahi Formation, and may well have reached the ground surface by way of fault planes of that age.

STRUCTURE OF TERTIARY ROCKS

The dips and faults of the Tertiary rocks are presumed to result from the Kaikoura Orogeny (of Taranaki to lower Wanganui age).

Dips

The coal seam and the base of the Whangarei Limestone dip eastwards at 8° to 9° (Figs 3a, 3c). The average dip direction over New Kamo No. 3 Mine is about 080°.

Faults

The most continuous faults strike within 20° of true north, although a major east-striking fault limited New Kamo No. 3 Mine on the northern side (Fig. 2). The plane of one major fault underground dipped at 85° towards 080°. No slickensiding was evident, but the steepness of the plane suggests that the fault was essentially transcurrent (Anderson, 1942). The plane of another major fault dipped at 72° towards 072°. The Harbour Fault, which limits the Kamo Coalfield to the east and has an upthrow of about 1,000 ft in that direction, was mapped by Ferrar (1925, Whangarei S.D.) as striking at about 150°.

The strikes of subsidiary faults underground average 035°. The dips of their planes range from 50° to 60°, the faults themselves are normal, and slickensiding shows that the movement was vertical rather than horizontal.

Joints and Veins in Coal

Calcite veins are common in the roof and in the coal, especially in the eastern part of the mine where the limestone and calcareous sandstone cover is greatest. Their strike average 038° ± 20°, which agrees well both with the direction of normal faulting and with the direction of the cleat in the coal (042° ± 13°). Less well defined joints in the coal (the "end") strike at 125°.

Interpretation

The strike of normal faults, cleats, and veins (035° to 042°, say averaging 038°) will be at right-angles to the direction of maximum tension, and hence parallel to the direction of principle horizontal stress (Fig. 6). Wellman (1954, pp. 201-2) deduced a value of 057° for the direction of principal horizontal stress in the Waihi Mine area. He followed Macpherson (1946, map 2) in assuming that the Cape Colville Peninsula may be interpreted as a major anticline of late Tertiary age, with an average strike of 155°. This figure is for the

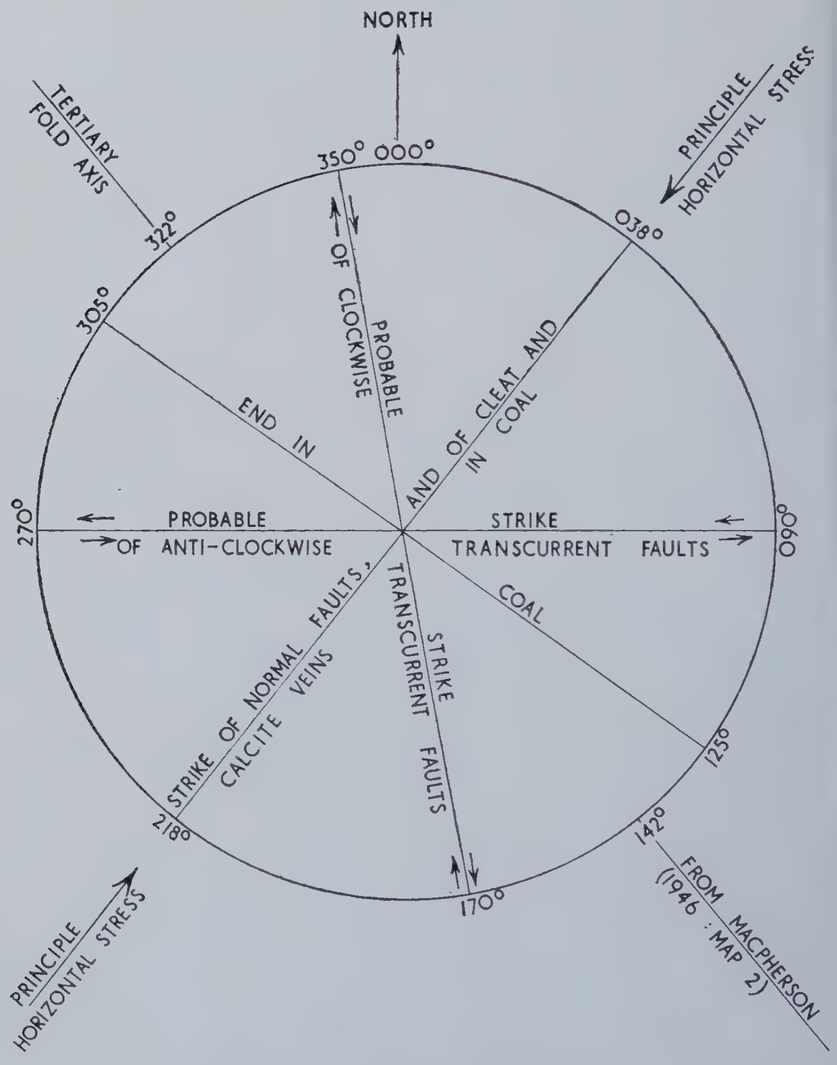

NORTH
350° 000°
038°
090°
125°
142°
170°
218°
270°
305°
322°
TERTIARY FOLD AXIS
PRINCIPLE HORIZONTAL STRESS
PROBABLE STRIKE OF CLOCKWISE TRANSCURRENT FAULTS
PROBABLE STRIKE OF ANTI-CLOCKWISE TRANSCURRENT FAULTS
END IN COAL
STRIKE OF NORMAL FAULTS, AND OF CALCITE VEINS AND OF CLEAT IN COAL
FROM MACPHERSON (1946 : MAP 2)
PRINCIPLE HORIZONTAL STRESS

FIG. 6.—Structural directions at Kamo.

strike given on Macpherson's map for the Coromandel-Colville end of the peninsula, and agrees well with the strike of a Tertiary anticline at Torehina (Kear, 1955, Fig. 1). Near Waihi the strike would be between 160° and 165°—say 162°. At Kamo, a strike of a hypothetical "Tertiary Fold Axis" may be similarly inferred from Macpherson's map as 142°.

Wellman inferred that a fault at Waihi, striking at 185°, was clockwise transcurrent. At Kamo the most likely transcurrent fault is that with a plane dipping at 85° towards 080°. From its relation to the strike of normal faults, it should be clockwise transcurrent. The strike of anticlockwise transcurrent faults should be at an equal angle on the opposite side of the strike of normal faults, i.e. 128° — (170° — 128°) = 086°. The known fault striking about 090° therefore could well be anticlockwise transcurrent. Table 3 compares the strikes of faults and fold axes between Waihi and Kamo.

TABLE 3.—Comparison of Various Structural Strikes Between Waihi (Wellman, 1954) and Kamo.

	Strikes of Faults, etc.				
				Transcurrent Faults	
Locality	Normal Faults, Joints, etc.	Normal Faults + 90°	Fold Axes (strikes of MacPherson's Arcs, 1946)	Clockwise	?Anti-clockwise
Waihi	057°	147°	162°	185°	—
Kamo	038°	128°	142°	?170°	?090°
Angular difference between values at Waihi and Kamo	19°	—	20°	15°	—

The "fold axis" strike obtained from Macpherson's map for the Waihi area is 20° greater than that obtained for the Kamo area. This difference is clearly reflected in the differences (15° — 19°) for the strikes of faults.

A difference of about 15° exists at both places between the strike of fold axes deduced from Macpherson's map and the theoretically identical value obtained by adding 90° to the strike of normal faults. The significance (if any), of this difference cannot, however, be assessed from only two measurements.

Mineral Water

The Kamo Springs, 1 mile north of the township, are well known, and analyses of their carbon-dioxide impregnated "soda-waters" have been published (Ferrar, 1925, pp. 123-4). Artesian "soda-water" was encountered in the old drillhole 33, and in the newer drillhole 28. In the latter, 230 gallons of water per minute flowed from crystalline limestone and overlying sandstone at 357 ft to 371 ft, with a greater artesian head than 20 ft. Its temperature was measured as 76° F, compared with 60° F for the water in nearby Brewery Creek.

COAL

Quality

Nineteen face samples were collected from 14 sampling positions throughout Kamo Mine in 1954 (Fig. 3b, and Table 4). The average values for the proximate analyses on air-dried coal were (approximately):

Moisture	Volatile Matter	Fixed Carbon	Ash	Sulphur	Calorific Value
8½%	41½%	41½%	8½%	4%	10,750 B.t.u./lb

Samples were carefully collected from freshly broken faces to ascertain the bed moisture of the coal. This was shown to be 9·4% (10·4% on an ash-free basis). The calorific value on a bed-moisture ash-free basis averaged 11,650 B.t.u./lb. Thus, the coal is of Sub-bituminous A rank on the A.S.T.M. classification.

The most variable factor in the coal analyses was the ash content, which ranged from 2·7% to 15·0%. The lowest values were found generally in the western part of the mine, and especially where the limestone cover is thinnest (Fig. 3b). Calcite veins and fine stringers are common in the coal, and the field suspicion that these represented a considerable proportion of the ash was confirmed by acid washing at Dominion Laboratory, D.S.I.R. There, four samples that averaged 9·2% ash prior to washing averaged 5·4% only afterwards (Miss J. B. Ross, pers. comm)..

The relation between ash content and limestone presence can hardly be coincidental, and the theory that the coal in western New Kamo Mine is relatively calcite-free because of the lack of limestone cover, implies that the calcite veins elsewhere were deposited since the limestone was eroded in the west. The probability that deposition occurred during low sea-levels since the Kaikoura Orogeny is emphasised by the low ash content of coal drill-cuttings from 680 ft below sea-level in drillhole 27, despite the obvious chances of contamination in an uncased hole. At this depth the coal was probably always below the water table. The ash contents shown on Fig. 2b also show a slight tendency for a decrease towards the east where depths exceed 400 ft below sea-level.

The sulphur content of the lower seam is substantially less (1·15% in analysis N20/a206, Table 4) than is that of the upper seam. This is to be expected in those seams that are necessarily farthest below marine beds (see Wellman, 1952, plate XVIII, fig. 3).

Quantity (Reserves of Recoverable Coal)

At least 1,299,875 tons of coal have been mined from the Kamo Area (Fig. 2). Since Hay's historical summary (1947, p. 173) the New Kamo Mine had increased its total output to 1,002,067 tons of coal up to 1955 when operations ceased, and Kamo Potteries worked 682 tons

TABLE 4.—Analyses of coal from New Kamo No. 3 Mine (by Dominion Analyst). Locations of sampling positions are shown in Fig. 3b.

Field No.	Dominion Laboratory No.	Total Moisture (as sample at the face) (%)	Proximated Analysis (on air-dried coal)				Air-dried Coal	
			Moisture (%)	Volatile Matter (%)	Fixed Carbon (%)	Ash (%)	Sulphur (%)	Calorific Value (B.t.u./lb)
N20/a206*	AA 575-1, 2	10·3	8·2	40·5	40·6	10·7	1·15	10,550
N20/a208	AA 575-4, 5	8·6	7·5	42·4	38·8	11·3	4·81	10,750
N20/a209	AA 575-6, 7	9·0	9·1	40·3	40·0	10·6	4·06	10,240
N20/a210	AA 575-8	7·6	7·4	43·2	37·8	11·6	4·69	10,470
N20/a211	AA 575-9	8·5	7·8	41·9	35·3	15·0	5·67	9,540
N20/a212	AA 575-10	8·2	7·9	42·7	39·0	10·4	4·79	10,570
N20/a213	AA 575-11	—	9·0	40·9	46·1	4·0	3·82	11,350
N20/a214	AA 575-12	9·7	8·6	40·1	42·6	8·7	2·52	10,640
N20/a215	AA 575-13	10·3	8·8	42·6	39·4	9·2	3·69	10,670
N20/a216	AA 575-14, 15	10·6	8·8	41·8	43·9	5·5	4·81	11,200
N20/a217	AA 575-16	—	9·4	40·6	47·3	2·7	3·89	11,460
N20/a218	AA 575-17	10·9	8·8	41·5	43·8	5·9	3·58	10,880
N20/a219	AA 575-18	9·5	8·6	42·5	45·2	3·7	3·27	11,540
N20/a220	AA 575-19	—	9·4	39·8	42·1	8·7	4·35	10,850

*Sample N20/a206 was from the lower seam. All others were from the upper seam.

of coal (in 1951, and 1953-5) from the Ruatangata area. Much coal still remains in mine pillars, and in the unworked lower seam where, for example, in New Kamo No. 3 Mine, the upper seam has been worked directly above it*. None of this coal, however, can be considered to be "recoverable" unless the present problems of de-watering can be overcome economically. Only virgin coal areas will therefore be considered here in assessing reserves.

West of the Ruatangata, Kamo, and Harrisons mine workings, coal thins and is expected to be unworkable (Hay, 1947a, pp. 178-9). Around the northern, eastern, and south-eastern sides of New Kamo Mine, the drilling of 1953-4 showed workable coal only in drillhole 27 (8 ft 6 in.). This, however, is downdip from the farthest inbye workings of the mine, and could not be reached except from those now flooded workings.

Thus, only two areas of unworked coal remain—the one between New Kamo No. 3 Mine and the older Kamo Nos 2 and 4 miles to the west, and the other between the West Drive of New Kamo No. 3 Mine and Harrisons Mine.

The first area is limited by faults to the east, north, and west, and may well be faulted internally. Coal is probably too thin to be workable north of drillhole 70, and from here to No. 3 drive the area comprises about 10 acres. Combined seam thicknesses range from 6 ft to 31 ft in this area, and average 18 ft. Allowing 1,500 tons per foot acre, a 10% loss for faulted ground, and a rate of extraction of only 33% (due to thick seams, a thin parting, and the known poor total extraction rates near Kamo), roughly 80,000 tons of "extractable" coal appear to be present.

The second area is limited to the north by New Kamo Mine, to the west by Harrisons Mine, and to the east and south by coal thinning. Leaving a barrier 1 chain wide alongside old workings, about 15 acres may be coal-bearing. Coal thicknesses range from 6 ft to 15 ft and probably average about 8 ft. Here a slightly higher extraction rate—say 35% to 40%—would probably be attainable with a thinner seam, and again roughly 80,000 tons of "extractable" coal appear to be present.

Thus, two areas of virgin coal remain at Kamo, each containing roughly 80,000 tons of workable coal. Both, however, are downdip of flooded mine workings, and could not be worked without adequate safeguards, which may or may not be possible.

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*Turner *et el.* (1957, p. 137) record 350,000 tons of coal as being available for recovery following possible de-watering to 45 ft below sea-level, with a similar additional quantity available following complete de-watering. Further coal is "available" in pillars of other flooded mines (e.g. Kamo No. 4).

The thickness of the lower seam is not known under much of the mine. However, the N.Z. Mines Statement for 1955 reported (pp. 72-3) that 5 drillholes in the Middle Section showed this seam to be unworkably thin, whilst others, in the Doels Dip area, showed 1 ft 8 in., 4 ft 1 in., 5 ft 8 in., and 10 ft of coal below a parting that ranged from 3 ft 2 in. to 18 ft 6 in.

To summarize: a large unestimated quantity of coal exists as pillars in flooded mine workings, and 80,000 tons of possible extractable coal exists in each of two virgin areas. The working of all coal, however, is dependent upon safe yet economic mining methods being developed that will enable either flooded mines to be re-entered or new mines to be commenced downdip of those that are already flooded. Until evidence is forthcoming that such methods are likely, no reserves of workable coal can be considered to be present at Kamo.

FLOODING OF NEW KAMO MINE

Inflow of Water

The quantity of water pumped from New Kamo No. 3 Mine was originally relatively small. The commencement of pillaring in two areas in the Middle Section (Fig. 2) in March 1955, however, caused more water to enter the mine at those points, initially through fractures that were observed to have been caused by pillar-falls. The quantity gradually increased through 300 gallons per minute (g.p.m.) in August, to 800 g.p.m. at the end of October 1955.

On 12 November the flow was measured in V-notches, as it ran down to the lowest workings, as 1,200 g.p.m. The next day the inflow increased appreciably and was re-measured as 2,500 g.p.m. by calculating the volume of mine workings flooded in a given time. On the night of 15-16 November the flow was calculated as 3,500 g.p.m. by timing a 60 ft vertical rise and assuming an average cross-section of the underground workings to be 60 sq. ft. On 16 November the rises through two vertical heights of 10 ft were timed after the workings had been hurriedly surveyed to obtain approximate cross-sectional areas. New workings averaged 63 sq. ft and old workings 55 sq. ft; but both 10 ft rises included small pillared areas that were of uncertain volume. Flows of 5,000 and 5,100 g.p.m. were calculated; and these were apparently increased to nearly 7,000 g.p.m. by midnight 16-17 November.

Thus, although the calculations were liable to considerable error throughout, it is quite clear that the inflow increased from a relatively small amount to over 2,000 g.p.m. by 13 November, to about 3,500 g.p.m. by 16 November, and to 5,000 g.p.m. or possibly somewhat more by 17 November. The water level would have been about 500 ft below the mine portal on the latter occasion. Subsequently the inflow gradually reduced as the mine flooded further, and the water was rising only slowly when the pumps were installed in No. 3 Drive in an attempt to de-water the mine. By that time the water reached a point 48 ft vertically below the mine portal (i.e. 267 above sea-level).

Initial Effect on Surface and Ground Water

Local residents report that when Kamo No. 4 Mine flooded, wells in the township went dry temporarily.

A spring on the southern side of Mt. Denby gives rise to a stream that flows south-east to just beyond drillhole 35 and then north-east to join Waitaua River between drillholes 13 and 33 (Fig. 2). Immediately after the pillaring in the Middle Section of New Kamo No. 3 Mine (which was closely below this area) the spring went dry and the stream was reduced to only a trickle, even in its lower part. The supply of artesian "soda-water" from drillhole 33, which had been interrupted previously after drillhole 28 struck its artesian flow, ceased once again at a time closely following the Middle Section pillaring.

Attempted De-watering, and Inflow Calculations

An attempt at de-watering commenced on 13 January 1956 by the leapfrogging of three pumps within the restricted space of No. 3 Drive. Measurements of pumping rates, when the water level was reasonably static for a prolonged period, allowed the inflow to be calculated. Hardie (1956) used three such reliable measurements to establish

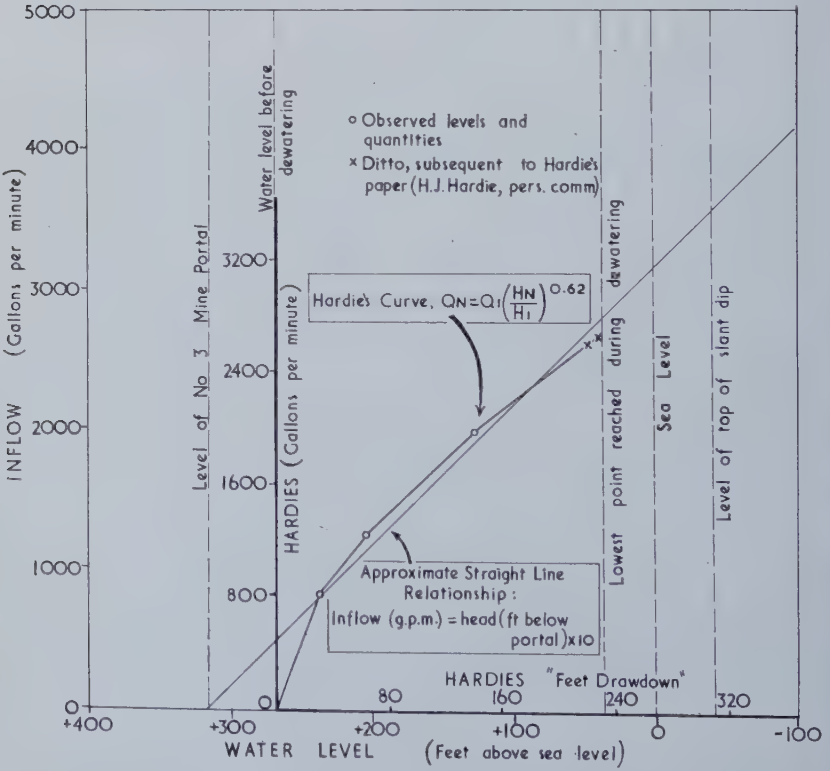

FIG. 7.—Relation between water level and inflow during the attempted de-watering of New Kamo No. 3 Mine. The diagram is based upon an original curve (Hardie, 1956) with extra points added from data supplied by Mr H. J. Hardie (pers. comm.).

a relationship between the quantity (Q, in gallons per minute) and the head (H, in feet below the starting point of 48 ft below the mine portal). He expressed the equation of the curve (see Fig. 7) as: $Q_X = Q_1 \ (H_X/H_1)^{0 \cdot 62}$. Subsequently two further measurements were made which fitted the curves closely (Fig. 7).

If the drawdown be measured from the mine portal, rather than from the point at which de-watering started (both of which points are arbitrary from a hydrological point of view) a simple relationship may be established between flow and head (see Fig. 7):

flow (in g.p.m.) = 10 × head (in ft vertically below mine portal)

The hydraulic conditions at the point of entry of water into the mine are uncertain, and would be especially so during continual pumping. Thus, the above relationship, although admittedly approximate, should be a useful rule-of-thumb guide for any further possible de-watering attempt. The inflow of 5,000 to 7,000 g.p.m. during flooding at about 500 ft below the mine portal, shows the broad validity of the equation.

After de-watering was eventually abandoned in November 1956, water levels were observed as the mine re-flooded (Fig. 8—based on data supplied by Mr H. J. Hardie, pers. comm.).

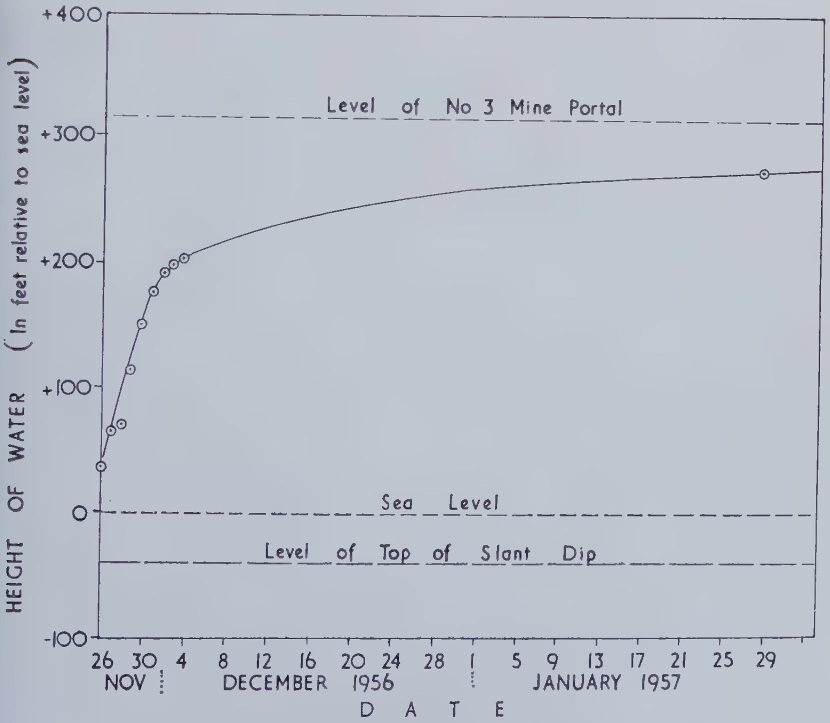

FIG. 8.—Rise in water level during re-flooding of New Kamo No. 3 Mine (data supplied by Mr H. J. Hardie, pers. comm.).

The de-watering did not cause the spring and stream flowing from Mt Denby, referred to above, to dry up for a second time. It did, however, cause a large reduction initially in the artesian flow, and subsequently in water level within drillhole 28 (Fig. 7). The water level in drillhole 25 was also dropped to 55 ft, but was observed to rise temporarily to 49 ft following heavy rain. These water levels cannot be normal, for hole 25, cased 30 ft or so into Waitakian sandstone, is only a few yards from Waitaua River, and only a foot or two above the water level therein. Water levels in drillhole 22 showed only seasonal variations, and did not appear to reflect the de-watering operations.

Conclusions Regarding Flooding

(1) Water entered the mine through fractures caused by pillaring that extended by themselves, or together with fault planes and joints, up into the fractured and cavernous Whangarei Limestone and upper Ruatangata Sandstone.

(2) The undoubted increase in rates of inflow during flooding can be accounted for only by scouring which enlarged the original fractures of entry.

(3) The drying-up of a spring and stream above the area of pillaring following the initial flooding of the mine showed that the water entering the mine was initially connected directly to the upper layers of the local groundwater. During de-watering the stream and spring were not noticeably affected, and it is likely that the direct connecting channels had been sealed by that time.

(4) The water that entered the mine was part of a vast body of underground water that was contained at least within sandstone and limestone cavities and in other rock voids, that extended over an area of many square miles (as shown by the considerable de-watering effect on drillholes as far apart at 25 and 28); that had a static head similar to that of the local groundwater (though locally it was artesian —e.g. drillholes 28 and 33); that was connected with the local sources of "soda-water"; and that was capable of re-charge from the surface at unknown points (as shown by the temporary rise in water level in drillhole 25 following heavy rain), and thus was of virtually limitless dimensions.

(5) During de-watering the mine acted very similarly to a normal water well, with a yield approximately proportional to the drawdown. Obviously the mine is by no means as simple as a well, and temporary blockages and increased scouring could make marked differences in pumping requirements. As a rule of thumb, however, it appears that, if any further de-watering should be attempted, about 10 g.p.m. will have to be pumped for each 1 ft of "drawdown" beneath No. 3 Mine portal. This approximation could be considerably too low, should scouring occur at the point of entry.

(6) Unless substantial blocking takes place at the points of entry into the mine, any de-watering operations would have to deal with a large quantity of water to reach even the Slant Dip. The advantage of

reaching that point is that some of the low-ash west section coal would be available for mining by that level, and some of the areas of virgin coal should be workable. However, the Slant Dip is 350 ft vertically below the mine portal, implying a pumping rate of the order of 3,500 g.p.m.

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GEOLOGICAL AND ARCHAEOLOGICAL INTERPRETATION OF A SECTION IN RANGITOTO ASH ON MOTUTAPU ISLAND, AUCKLAND

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Summary

A foredune section at Pig Bay, Motutapu, has been excavated to expose non-volcanic beach sand below a single Rangitoto ash layer which, in turn, is overlain by a series of wind-blown and water-laid sediments containing reworked ash. The date of the eruption was determined by carbon samples as A.D. 1188 ± 50 years. The sediments above the Rangitoto ash include a number of well defined human occupation levels, some of which have yielded adzes of moa-hunter type.

INTRODUCTION

Motutapu Island is formed mainly by the bedded greywacke sandstones and argillites, with minor cherts and spilites, which are basement rocks elsewhere in the Auckland area. On the western side of the island, and near the northern end, fossiliferous sandstones and siltstones of Waitemata Group occupy coastal strips. Basaltic ash from the adjacent vent of Rangitoto Island, lying to the south-west (Fig. 1), covers a large area on Motutapu; the ash layer averages 2 to 3 ft in thickness on the western parts of Motutapu, but becomes very thin at the northern end away from the parent vent. On the eastern side of Islington Bay, which separates the southern parts of Motutapu and Rangitoto islands, the ash clearly overlies a post-Flandrian marine sand terrace at 8 ft above mean sea-level, indicating a fairly recent age for the eruption. On the higher parts of Motutapu the ash cover has undergone varying degrees of stripping so that weathered rocks of Tertiary and older age are exposed on hill slopes. No comparable ash bed has been seen on Rangitoto where presumably it has been covered by the voluminous flows of olivine basalt extruded in a later stage of the eruptive cycle.

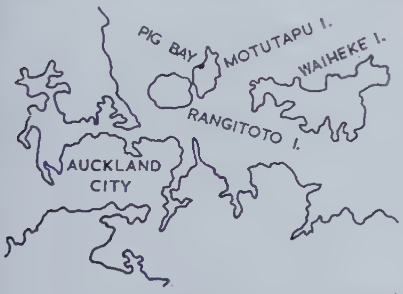

Fig. 1.—Locality map for Rangitoto, Motutapu, and Pig Bay. Scale 1 in. = 17 miles.

N. Z. J. Geol. Geophys. 2 : 569-77.

During World War II numerous fortifications were constructed on Motutapu. Trenches were prepared on the foredune complex behind a small beach called Pig Bay, at the western end of Administration Bay (N38/422727P), and these were excavated in ash material containing numerous human occupation layers. At that time Mr J. T. Diamond observed the large quantity of stone artifacts on the site; this information was given recently to one of the authors (J.G.) who then visited the locality and later organized extended field excursions by the Auckland University Archaeological Society in order to undertake controlled excavations over a grid pattern.

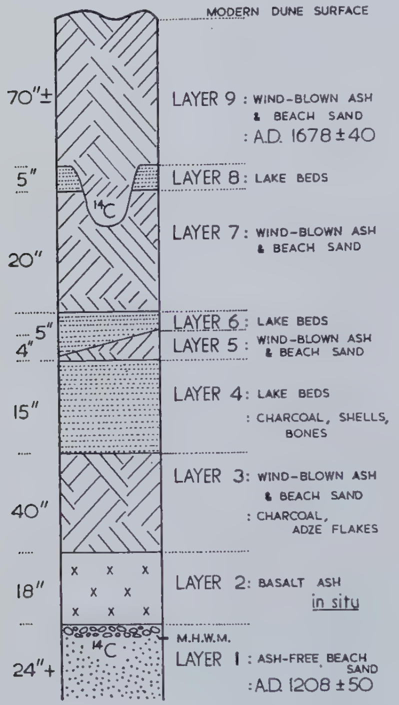
MODERN DUNE SURFACE
70"±
LAYER 9 : WIND-BLOWN ASH & BEACH SAND : A.D. 1678±40
5"
LAYER 8 : LAKE BEDS
14C
LAYER 7 : WIND-BLOWN ASH & BEACH SAND
20"
5"
4"
LAYER 6 : LAKE BEDS
LAYER 5 : WIND-BLOWN ASH & BEACH SAND
15"
LAYER 4 : LAKE BEDS : CHARCOAL, SHELLS, BONES
40"
LAYER 3 : WIND-BLOWN ASH & BEACH SAND : CHARCOAL, ADZE FLAKES
18"
LAYER 2 : BASALT ASH in situ
M.H.W.M.
14C
24"+
LAYER 1 : ASH-FREE BEACH SAND : A.D. 1208±50

Fig. 2.—Stratigraphic succession exposed on the seaward face of the foredune at Pig Bay. Locations of dated carbon samples are shown at the top of layer 1 and at the base of the *hangi* cut through layer 8.

The stratigraphic section (Fig. 2) was prepared from the first face to be excavated on the seaward side of the foredune which at present is undergoing tidal erosion. The natural exposure on the eroded dune shows only the upper half of the section, but the lower part was revealed by extensive digging down to a level a little below high tide mark.

Geology of the Section

The section is described below in terms of the layers drawn and numbered in the stratigraphic column (Fig. 2). These layers have been defined on the basis of pyroclastic, fluvial, or subaerial origin; detailed archaeological descriptions may require further subdivision.

Layer 1: Ash-free Beach Sand

The base of the section is formed by a golden-yellow ash-free sand, the depth of which could not be determined. Its upper surface lies approximately at modern high water level and the interface against the overlying basaltic ash is sharp and well defined by a veneer of rounded beach pebbles of greywacke (Fig. 3). The sand has characteristics which make it quite different from any other sediment in the section. These features are complete absence of basaltic materials, a dominance of subangular grains of quartz and acid plagioclase feldspar, and numerous small pebbles of greywacke and distinctive pink chert along with abundant abraded shells and shell fragments of pelecypods and gastropods.

A source for the inorganic components of the sand is readily found in the Tertiary sediments forming the coastline to the west and in the greywackes and argillites which crop out along the eastern side of Administration Bay where a large mass of bedded pink chert occupies part of the shore platform.

Because the sand lacks basalt fragments and has an upper limit at high tide mark, it has been interpreted as the beach deposit which existed in the littoral zone immediately prior to the ash explosion on Rangitoto Island.

The carbon date of 750 ± 50 years before present (N.Z. ^{14}C No. 220, Fergusson and Rafter, 1959) (A.D. 1208 ± 50) for this non-volcanic beach sand was obtained from shells incorporated within the uppermost part of the layer.

LAYER 2: RANGITOTO ASH

The ash overlies the beach sand as a compact and coherent massive dark grey layer averaging 18 in. in thickness. The upper surface is gently undulating, but quite distinct, and the rock requires gentle rubbing between the fingers in order to break it down to individual particles. More than 80% of the ash is made up of green to brown curvilinear basaltic glass shards, with refractive index $1 \cdot 598 \pm \cdot 002$, and with outlines which are very sharp and commonly delicately spinose. Gas bubbles and vesicles are common in the glass fragments, in addition to crystal inclusions of pyroxene, ore, olivine, and intermediate plagioclase feldspar. These minerals, as separate fragmentary crystals, make up the remainder of the ash layer.

Bedding, sorting, and rounding are lacking as textural features in the basalt tuff and this evidence, together with the absence of alongshore beach detritus in the form of quartz, acid feldspar, or pink chert grains, indicates that the ash layer exposed in the section has not been disturbed or reworked.

LAYER 3: WIND-BLOWN ASH AND BEACH SAND

The dune beds that overlie the ash layer are loose free-running sands composed mainly of basaltic material with significant amounts of pink chert, quartz, acid feldspar, and shell fragments as small rounded grains. This layer is 40 in. thick and it displays large-scale wind-bedding as well as a high degree of sorting in the component sand. The crystal and glass fragments show clear signs of rounding, with pitted surfaces and smoothing of spinose edges and sharp corners.

A sand dune phase immediately following deposition of the ash seems to be an orderly sequence of events, for the shore of that time temporarily must have been extensively prograded by the excessive quantity of volcanic sediment suddenly made available in the ash shower. Dune formation and subaerial inland migration by admixed ash and original beach sand satisfactorily accounts for the presence of layer 3.

LAYER 4: LAKE BEDS

Horizontal, finely stratified muddy beds of basaltic ash cut across the top of the dune sands of layer 3 and continue upwards for 15 in. to be covered in turn by further dune sands in layer 5. These aqueous sediments contain almost exclusively unsorted basaltic materials of small grain size which lack the coherency and spiny texture of the primary ash layer. Nevertheless, individual beds are fairly compact, and the muddy nature of the sediments together with the absence of beach-derived chert and quartz grains points to an inland source of supply from ash lying on the hill slopes. The deduction that this material has been washed down seasonally into a temporary lake, which was formed by sand dune damming of Pig Bay stream, is supported by the presence of lens-and-pocket bedding and wedging of the thin beds. Charcoal fragments, broken shells, and fish and dog bones within these lake beds are clear indications of human activity on the site at this time. Similar occupational remains are present in all the succeeding layers (5 to 9) in the section.

It seems likely that a large mass of dune sand enclosed an extensive high level lake over and seaward of the present Pig Bay foredune area. Evidence for this is the height of the uppermost subaqueous bed in layer 4 at approximately 6 ft above high water mark, and the lack of wind-blown detritus which at this stage could not advance very far inland across a sheet of water dammed behind the outlying beach.

UPPER LAYERS, 5 TO 9

A phase of sand dune advance is represented in layer 5 which has all the characteristics of the lower dune layer 3. Lake beds appear again in the thin band of layer 6 which is covered by 20 in. of wind-blown sand in layer 7. The highest subaqueous bed in the section appears in the 5 in. layer 8 which is an important datum line, for a *hangi* (cooking pit) cut down through this layer into the underlying dune sands (7) provided charcoal (N38/520) in burnt twigs with a carbon date of 280 ± 40 years before present (N.Z. ^{14}C No. 221, Fergusson and Rafter, 1959) (A.D. 1678 ± 40).

The topmost layer 9 consists entirely of wind-blown sand made up in the usual way of ash particles and material from the older rocks in the area.

GEOLOGICAL CONCLUSIONS

(a) The section given above represents the sedimentational history of the Pig Bay foreshore over the last 700 to 800 years. The shore profile formed by the non-volcanic sand of layer 1, which was in existence about the year 1200 A.D., was greatly altered by a voluminous ash shower which blanketed the area and formed a compact tuff deposit (layer 2) at the back of the beach. This sudden influx of volcanic debris caused progradation of the shoreline, and a sandy foreland, consisting of ash mixed with original beach sand, was built out. Migratory dunes (layer 3) composed of these mixed sediments moved inland across the line of the buried pre-volcanic beach and covered the undisturbed ash bed.

Sand dune accumulation was probably rapid and within a short period of time after the eruption Pig Bay stream was blocked and ponded at the mouth. A temporary freshwater lake formed and was gradually infilled to a level 6 ft above high tide mark by ash fragments (layer 4) washed down from the inland hill slopes. Wind-blown sand (layers 5, 7, 9) continued to fill the lake hollow during dry seasons and raised the level of deposition of subsequent subaqueous beds of ash (layers 6, 8) brought in from the adjacent hills. Shortly afterwards the Pig Bay stream must have regained its original lower profile by cutting down through the sand dune barrier, for lake beds are absent above layer 8 and dunes form the modern topography. Tidal scour along the foreshore at present is continuing to erode the seaward face of the dune belt.

(b) Only one primary ash layer appears in the section and a similar feature has been found in a number of other exposures on Motutapu. This suggests that during the eruptive history of Rangitoto there has been only one major explosion which must have occurred at an early stage since no comparable widespread ash beds are exposed above the lavas that form the greater bulk of that island. It is possible that this explosion took place when Rangitoto volcano first commenced activity, for small blocks of Tertiary sandstone are fairly abundant in the ash layer on Motutapu near to Islington Bay. The absence of such accidental materials in the ash exposure at Pig Bay must be due to the greater distance from the active vent.

Two other lines of evidence indirectly favour the possibility that the single ash eruption was indeed the first phase of activity at Rangitoto: (i) the complete lack of volcanic sediment from basalt, such as glass, olivine, intermediate plagioclase or pyroxene grains, in the beach sand of layer 1 would be difficult to explain if any form of volcanic activity had been taking place on Rangitoto either at that time or previously; (ii) many of the volcanoes on the Auckland isthmus have an eruptive history like the one that seems to be indicated for Rangitoto, namely an initial violent explosive phase with emission of finely comminuted basaltic ash and accidental ejecta, followed by the construction of a scoria cone and the extrusion of lava flows.

(c) The carbon sample (N.Z. ^{14}C No. 220), consisting of shells from the upper part of the ash-free beach sand (layer 1), has provided an age which defines the oldest possible date for the ash shower and probably for Rangitoto volcano; i.e. 750 ± 50 years before present (A.D. 1208 ± 50).

An additional carbon sample (N.Z. ^{14}C No. 222) in the form of charred twigs was taken from the base of the ash bed, and above the soil of weathered greywacke sandstones, at the top of a road cutting on the spur immediately east of Pig Bay. The age of this sample is 770 ± 50 years before present. Assuming that the charred twigs represent a vegetation carbonized directly by the ash shower, an absolute date is obtained for the eruption as 1188 A.D. ± 50 years. This absolute date lies within the range of error for the shell sample (N.Z. ^{14}C No. 220) from the ash-free beach sand in layer 1 where the oldest possible date for the eruption was 1208 A.D. ± 50 years.

ARCHAEOLOGY OF THE SECTION

Firm assessment of the archaeological stratigraphy must await completion of excavations which have at present reached the top of layer 3 over an area of about 70 square yards. This assessment will inevitably require subdivision of the described section in Fig. 2, but for present purposes the geological divisions can profitably be employed.

LAYERS 1 TO 2

A small trench (Fig. 3) was opened up some distance from the main excavations at a point where the overburden is relatively shallow. Apart from the original excavation on the foredune face, only here has ash-free sand been reached. Amongst the shells and pebbles lying immediately beneath Rangitoto ash was a fist-sized lump of chipped greywacke, much rolled but apparently flaked by human agency.

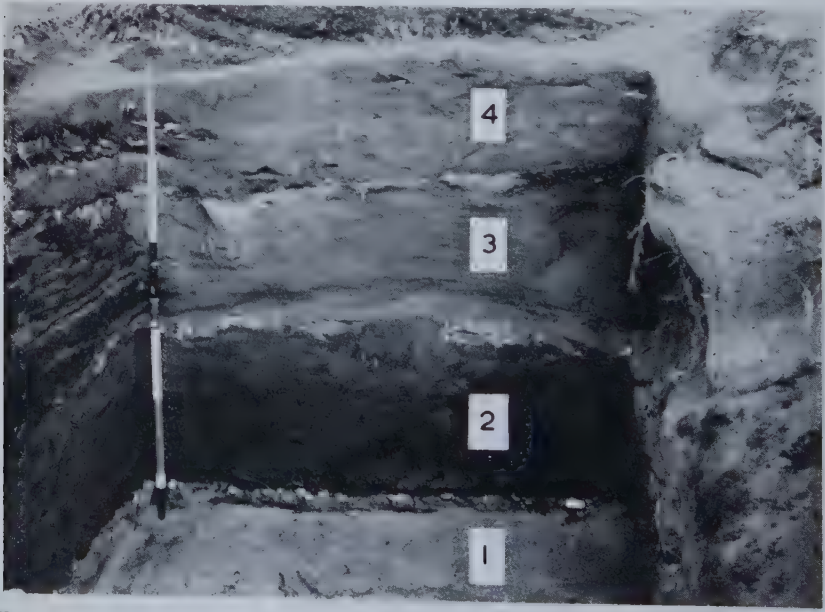

FIG. 3.—A trench, excavated about 25 yards north-east of the main exposure of Fig. 2, showing layers 1 to 4. Marker pole divisions in feet; shells and pebbles visible at the top of layer 1.

LAYER 3

In the same trench charcoal, an unfinished broken adze, and humanly struck flakes of greywacke were found in the top 18 in. of the post-eruption dunes.

LAYERS 4 TO 8

The most remarkable feature of the archaeology is the stratification throughout the lake beds and intervening wind-blown ash series of numerous culture layers. The beds contain evidence of cooking and toolmaking activities. Over a large part of the site, however, they have been so cut about that the correlation of beds is difficult. In the eastern third of the excavated area up to six levels of occupation are present, sealed in for the most part between layers of water-laid re-worked basaltic ash, and representing occupation of the lake margins between periods of flooding.

LAYER 9

Though capable of subdivision, layer 9 may be treated here as an archaeological as well as a geological unit. The intensive and varied occupational character of the underlying deposits ceases with layer 8, and layer 9 is characterized by a few thin middens of shell and fish-bone, with virtually no associated material culture.

ARCHAEOLOGICAL CONCLUSIONS

(a) The possibility of human occupation on Motutapu before the eruption of Rangitoto, suggested by the flaked greywacke recovered by excavation, is strengthened by similar discoveries reported by Mr R. Sunde from a beach site on the north-west coast of the island.

(b) As it is improbable that people would live close to the pyrotechnic display of an erupting basaltic volcano, evidence of human occupation in upper layer 3 and successive beds suggests that the process of cone building and flow emission of lava which accounts for the bulk of Rangitoto took place quite quickly after the initial ash eruption, and was completed by the time level represented in the upper part of layer 3.

(c) Intensive and recurring occupation of the site was co-eval with the freshwater lake, the period of existence of which falls within the limits of the radiocarbon dates: A.D. 1208 ± 50, and 1678 ± 40.

(d) These dates are of considerable archaeological significance. At present the prehistoric culture sequence in New Zealand is known only in its earliest and latest stages. At the one end the moa-hunter stage is dated (N.Z. ^{14}C Nos 50, 58) as far back as 12th century A.D. in the South Island (Fergusson and Rafter, 1957) and is well represented in the North Island. At the other end the descriptions and collections of the late 18th century voyagers define the cultural manifestations of the latest stage. Archaeological material from the intermediate phase, although present in museum and private collections, cannot be recognized for what it is. As a result the course and causes of the considerable changes between the culture of the moa-hunter and the late Maori stages are unknown.

The radiocarbon datings show that the major cultural deposits on the Motutapu site belong to this critical phase. These deposits disclose a stratified series of occupation levels particularly rich in adze material; and New Zealand adzes, the most prolific item in the Maori archaeological record, exhibit sufficient variation in form to be one of the most sensitive measures of culture change.

(e) Anything beyond the most provisional remarks about the significance of the material recovered from the stratified deposits would, however, be inadmissible.

The adzes from the lowest levels in layer 4 include two types characteristic of the moa-hunter period in New Zealand and allegedly absent from late deposits. In Duff's (1956) adze classification these are types 1A (tanged with quadrangular cross-section) and 4A (tanged with triangular cross-section of the hog-backed variety).

Mr Diamond's collection, made at the time of the exposure of the site during the war, contains besides these two types the upper half of a finished adze of the rarest but most diagnostic type the moa-hunter phase has to offer, the so-called side-hafted adze. Mr Diamond's adzes come from layer 4 in the section described above.

It would appear then that the people who camped behind the Pig Bay dunes soon after the eruption of Rangitoto were of moa-hunter stock, so that the radiocarbon date for the eruption becomes the first date for any phase of moa-hunter occupation in the North Island. This date accords well enough with the South Island dates.

What is surprising is the persistence into layers equivalent, it would seem, to the geologist's 6 and 7, of adze type 1A, with none of the modifications that might theoretically be expected to have occurred at so apparently advanced a stage in the culture sequence.

(f) Evidence of occupation becomes much sparser above the horizon marked by the latest lake-laid ash deposit and dated by the *hangi* pit dug through it.

At a point midway in the thick deposit, layer 9, an iron file sitting on a subsidiary interface testifies to the amount of wind-blown sand that has built up during the European period.

ACKNOWLEDGEMENTS

The writers wish to express their gratitude to Mr W. Ambrose and members of the Auckland Univesrity Archaeological Society whose efforts have made possible extensive excavations on the site at Pig Bay. The co-operation of the Nuclear Science Division of the Department of Scientific and Industrial Research in making age determinations on the carbon samples is deeply appreciated.

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STRATIGRAPHY OF NEW ZEALAND'S CENOZOIC VOLCANISM NORTH-WEST OF THE VOLCANIC BELT

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Summary

The several methods for dating volcanic formations are reviewed. They are: superposition (including the relationship to eustatic terraces), local and distant fossils, radiocarbon, petrology, paleomagnetism, weathering and erosion of rocks, and erosion of cones. The stratigraphic data of the many volcanic formations north-west of the Volcanic Belt are summarized in a figure and a table.

The distribution of andesites, dacites, and rhyolites (as opposed to that of basalts) tends to be parallel to the main arcuate structures of the North Island. For any single lithologic type, the younger volcanic arcs tend to be to the east, and within any one arc the latest volcanic foci tend to be in the south. The sequence of volcanism is inferred to be: andesite (oldest), dacite, rhyolite, and basalt (youngest); with tectonic activity extending possibly from as early as late in the andesite volcanicity, through possibly into the period of rhyolite eruptions. The fact that the present-day eruptions at Tongariro National Park are andesitic may be explained by a southward shift of volcanic foci to that area, rather than by an assumption that andesite eruptions are a late phase of volcanism.

INTRODUCTION

New Zealand's Cenozoic volcanic rocks are best known from the active Volcanic Belt that extends from Tongariro National Park to White Island. Many more, however, are present to the north-west of that belt (Fig. 1), and, since their relationships to non-volcanic rocks can be studied in some areas at least, their stratigraphic distribution is more easily worked out. Study of their stratigraphy may prove valuable in the more difficult problems of the Volcanic Belt itself.

The present paper was presented at the 1958 Adelaide Congress of the Australian and New Zealand Association for the Advancement of Science. It includes brief comments on the several methods for dating volcanic formations, and presents a table and maps to illustrate their stratigraphic distribution. Tentative conclusions are drawn also about the movements of volcanic foci with time, the correlation of some volcanic formations, the sequence of volcanism and tectonic activity, and the application of that sequence to the Volcanic Belt.

DATING OF VOLCANIC FORMATIONS

Superposition and Relation to Terrace Levels

Brothers' (1954b) implication that terrace levels in Northland may be contemporaneous with those of Europe, because of the region's

N.Z. J. Geol. Geophys. 2 : 578-89.

relative tectonic stability, adds a valuable tool to the more normal methods of dating by superposition. The ages of basalts relative to terraces have already been deduced at Hokianga (Mason, 1953), in Franklin County (Schofield, 1958b, pp. 545–7), and at Kamo (Kear, 1959).

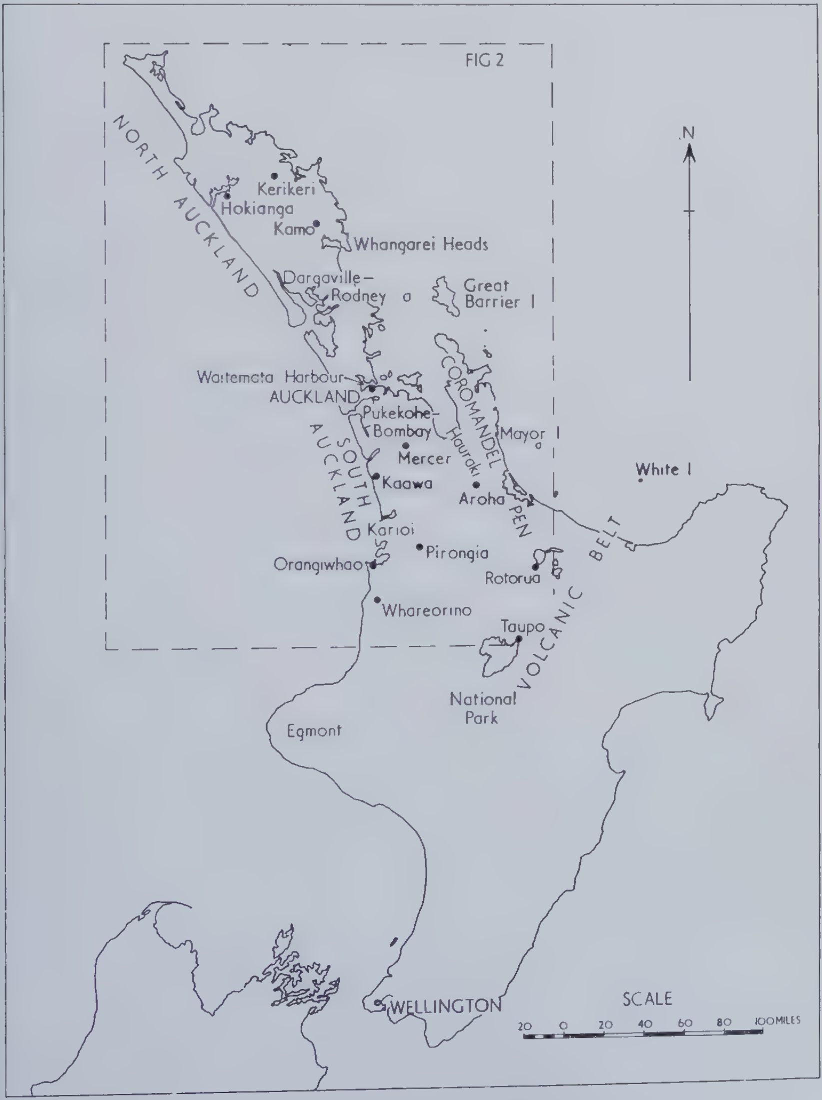
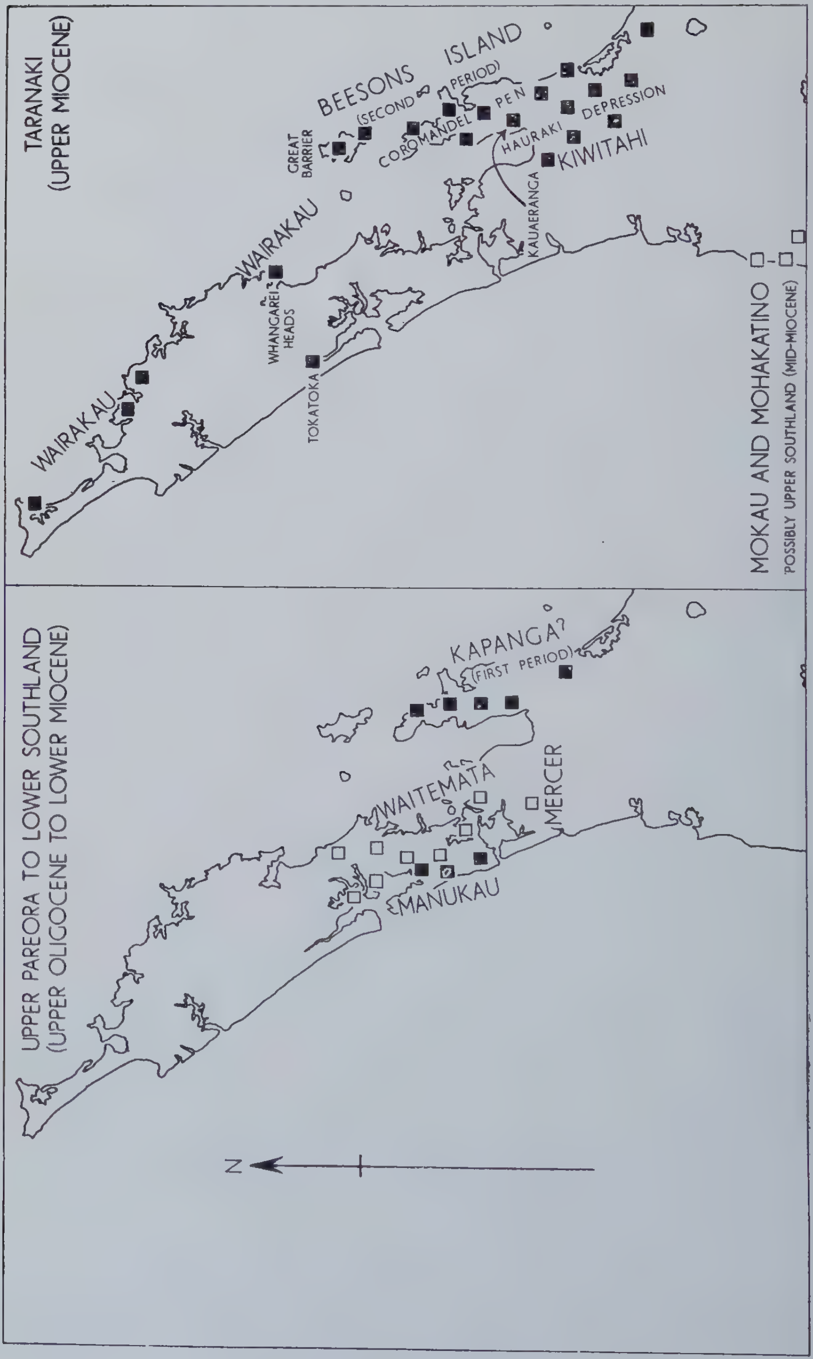


FIG. 1.—Locality map.


TARANAKI
(UPPER MIOCENE)
BEESONS ISLAND
(SECOND PERIOD)
GREAT BARRIER
COROMANDEL PEN
HAURAKI DEPRESSION
KIWITAHI
KAUAERANGA
WAIRAKAU
WHANGAREI HEADS
TOKATOKA
WAIRAKAU
MOKAU AND MOHAKATINO
POSSIBLY UPPER SOUTHLAND (MID-MIOCENE)
UPPER PAREORA TO LOWER SOUTHLAND
(UPPER OLIGOCENE TO LOWER MIOCENE)
KAPANGA?
(FIRST PERIOD)
WAITEMATA
MERCER
MANUKAU
N

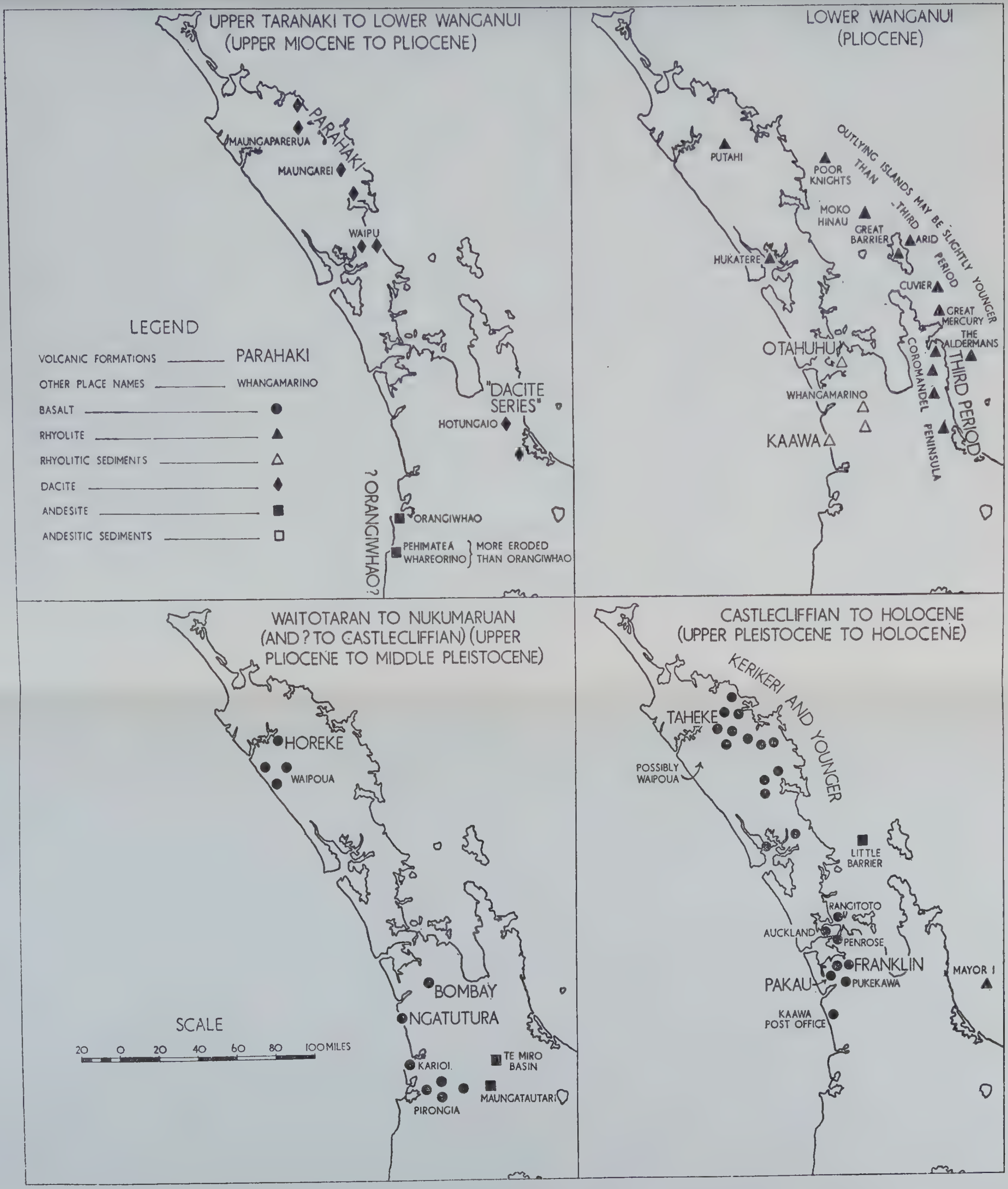


FIG. 2.—Stratigraphic distribution of upper Tertiary and Quaternary volcanic rocks, north-west of the volcanic belt. Since the present paper and figures were prepared, Cuvier Island has been visited by Messrs B. N. Thompson and B. C. Waterhouse, who report (pers. comm.) that it is an igneous-"greywacke" complex rather than a Pliocene-Quaternary acidic volcano, as indicated on (e.g.) the 1:2,000,000 Geological Map of N.Z. (1958).

Local Fossils

Marine fossils are occasionally interbedded with New Zealand's upper Tertiary and Quaternary volcanics (e.g., Waitemata Formation, Finlay and Marwick, 1948, p. 24), and elsewhere underlie them and may give useful limiting ages for eruptions (e.g., at Ruapehu, Fleming and Steiner, 1951). Plant fossils, and especially plant microfossils, however, are potentially even more useful. They have already provided some critical datings (e.g., Beesons Island Volcanics, Couper, 1953), and should yield more in the future. Even where formations are too young to contain extinct species, vegetational and climatic sequences may prove useful.

Distant Fossils

Datings that rely on fossils outside the immediate area of volcanism must always be tentative only, for the correlation of the volcanic products in a distant sequence is never certain (e.g., the dating of Pirongia, Kear, 1957b, pp. 678–80).

Radiocarbon

Radiocarbon is one of the latest tools to be used successfully in the dating of volcanic eruptions (e.g., Penrose basalt, Fergusson and Rafter, 1955), but it has at present a maximum age limit of about 45,000 years.

Petrology

Where fossil evidence is lacking, correlation of rock type is an old tool of the stratigrapher. Although it must be regarded with suspicion for long-distance correlation of volcanic formations, this method should be used in the absence of others (e.g., pumice in New Zelanad, Kear, 1957d). Grindley and Harrington's (1957) introduction of petrographic provinces for New Zealand is a most useful guide for short-distance correlation, since there is obviously a greater chance that petrologically similar rocks will be of similar ages if they are in the same province.

Paleomagnetism

In a study of the magnetic properties of ignimbrite sheets at Whakamaru, Hatherton (1954, p. 430) concludes that "if sufficient measurements are made it should be possible to group the sheets into eruptive periods, for the magnetic vector is variable in direction with time". More work along these lines appears desirable.

Weathering and Erosion of Rocks

While taking into account differences in lithology, topography, and climate, the degree of soil formation and weathering is an important factor in the dating of younger volcanic rocks; it is widely used, perhaps sometimes unconsciously. However, the similarity in the weathered appearance of Mesozoic and presumed lower to middle Pleistocene rocks suggests that this criterion is of value only in the dating of upper Pleistocene to Holocene volcanics. A comparison of the erosional features of volcanic rocks with those of nearby datable formations or surfaces, may give valuable evidence of age (e.g., basalts near Kaawa Post Office, Henderson and Grange, 1926, p. 72).

Erosion of Cones

Erosional stages of volcanic cones are thought to have useful age significance, provided allowance is made for differences in rock type, size and complexity of the cone, geological history, location, and climate. Two amendments are desirable to the age ranges originally deduced by the present author (Kear, 1957b).

Evidence presented below suggests that Tokatoka Peak (the type of the Skeleton stage) may be as old as Southland (lower Miocene).

The first activity of Pirongia Volcano (on the boundary between the Planeze and Residual Mountain stages) was probably in the upper Waitotaran. The evidence for this, based upon personal communications from Mr J. C. Schofield (stratigraphy), Dr R. A. Couper (paleobotany), and Dr J. J. Reed (petrology), will be published elsewhere.

The amended age ranges for the four stages are therefore: Volcano Stage, Holocene; Planeze Stage (showing some remnant of original cone form), Holocene to Nukumaruan or even Waitotaran (Holocene to upper Pliocene); Residual Mountain Stage, lower Wanganui, possibly to Taranaki, series (Pliocene, possibly to upper Miocene); and Skeleton Stage (volcanic necks and radial dykes), lower Wanganui to possibly Southland series (Pliocene to Miocene, possibly to lower Miocene).

STRATIGRAPHY OF VOLCANIC FORMATIONS

Figure 2 and Table 1 summarize the stratigraphy of volcanic formations north-west of the Volcanic Belt. All data that are considered to be significant are included, and no further comments will be made here.

CONCLUSIONS

Arcuate Structure

The distribution of the andesites, dacites, and rhyolites shows a strong tendency to be parallel to the main arcuate structures of the North Island (Macpherson, 1946, map 1). The distribution of Quaternary basalts, on the other hand, does not show this at all clearly.

Movements of Volcanic Foci with Time

Figure 2 allows some tentative conclusions about possible movement of volcanic arcs with time, and also about movement of volcanic foci along one particular arc with time.

The shift of the major andesitic arcs is eastward—Manukau Breccia in the lower Southland, to Beesons Island in the Taranaki. Rhyolitic eruptions in quantity (probably lower Wanganui) have been restricted to two arcs—one along the eastern side of Cape Colville Peninsula, and the other represented by offshore islands. Of the two, the latter appears the younger on physiographic grounds, especially as it includes Mayor Island (?Castlecliffian to Hawera) to the south. Again an eastward shift is possible. Among the basalts there is no consistent evidence of movement, since there is no obvious arcuate structure, but the oldest basalts (e.g., Ngatutura and Horeke) do tend to be in the west, and the youngest (e.g., Rangitoto) in the east.

A southward shift of the eruption of hornblende andesite is indicated by the fact that Orangiwhao appears more eroded than Pehimatea and Whareorino, and they in turn are undoubtedly older than Mt Egmont (in Volcano Stage), which may lie on the same arc to the south. A similar shift is noted in the Hauraki Depression, where the andesites to the north (e.g., Mangatangi and Pukekamaka) are eroded to the latest Residual Mountain or Skeleton Stage, while those to the south (e.g., Te Miro Basin and Maungatautari) are eroded only to the early Residual Mountain Stage. Mayor Island is at the southern end of an arc of rhyolitic eruptions that may well have lasted from the Opoitian-Waitotaran or Nukumaruan through to the Hawera. Finally, a southward shift of the foci of major rhyolitic eruptions, from the Cape Colville Peninsula in the lower Wanganui, to Taupo in the Holocene, has already been postulated (Kear, 1957d, pp. 967–9).

No single point is conclusive, but two conclusions, which must obviously be treated as broad inferences rather than as strict rules, may be drawn. For a single lithology, the younger volcanic arcs tend to appear farther east than the older ones, and the youngest activity within any one arc tends to be towards the southern end.

Correlation of Some Volcanic Formations

Although there is no certainty that all eruptions along one arc must have been contemporaneous, nor that volcanism must have progressed along it uniformly with time, two interesting points would result from the adoption of these theses. Firstly, Tokatoka peak in Northland would more probably be a correlative of the Manukau Breccia (Southland) than of Beesons Island Volcanics (Taranaki), and this would take the maximum age for the Skeleton Stage of cone erosion back to the lower Southland (lower Miocene). Secondly, the already uncertain age difference between Kapanga and Beesons Island volcanics would disappear—i.e., the Kapanga Volcanics would be of Taranaki age rather than a correlative of the Manukau Breccia. The evidence is far too slim yet for final adoption of either point, but the former has led to a tentative

TABLE 1.—Stratigraphic data for volcanic rock formations in area north-west of the volcanic belt.

Age						
European	New Zealand Series or Stage	Method of Dating	Volcanic Formation	Area and Volcanic Province (Grindley and Harrington, 1957	Petrology	Remarks (Cone erosional stages as in Kear, 1957b)
Pre-upper Oligocene	Pre-Hutchinsonian	—	—	—	—	No volcanics known, except possibly in Dannevirke lower Eocene)
Upper Oligocene	Hutchinsonian (upper Pareora)	Forams at Mercer (Mr N. de B. Hornibrook, pers. comm.)	Mercer Beds	South Auckland (Manukau)	Andesite	Thin tuff beds in sandstone and siltstone
Lower Miocene	Altonian (lower Southland)	Marine fossils (Finlay and Marwick, 1948, p. 24)	Waitemata Formation, Manukau	Northland and South Auckland (Manukau)	Hyalopolitic pyroxene andesite (Searle, 1944, p. 65)	Brothers (1954a) considered Waitemata Formation and Manukau Breccia virtually coeval
?Lower Miocene	?Altonian	Broad correlation with Manukau Breccia	Kapanga	Cape Colville Peninsula (Coromandel)	Pyroxene andesites, and less common hornblende andesite and dacite (Fraser and Adams, 1907)	Also known as "First Period Volcanics". Separation from Beesons Island Volcanics ("Second Period") uncertain, hence may be Taranaki
Upper Miocene	Taranaki	Forams (Finlay and Marwick, 1948, p. 25)	Mohakatino Formation	Taranaki (?Manukau)	Andesite	Andesite also near top of ?slightly older Mokau Group (Kear, 1957d, p. 864)
Upper Miocene	Taranaki	Plant microfossils at Great Barrier (Couper, 1953) and Kauaeranga (Kear, 1957a)	Beesons Island	Cape Colville Peninsula (Coromandel)	Pyroxene and hornblende andesites, rarer dacites (Fraser and Adams, 1907)	"Second Period Volcanics." Dr R. A. Couper's ages (on plant microfossils) of "Taranaki to lower Wanganui" rectricted to Taranaki to allow a lower Wanganui age for the overlying "Third Period Volcanics" (Kear, 1957d, p. 867). Cone remnants in Skeleton Stage
Upper Miocene	Taranaki	Correlation with Beesons Island	Kiwitahi	Hauraki Plains, etc. (Coromandel)	Pyroxene (Henderson and Grange, 1926, p. 26) and hornblende andesite	Cone remnants in late Residual Mountain (south) to Skeleton (north) Stages. The former may be Pliocene, but all are grouped together in Fig. 2
Upper	Taranaki	Correlation with Beesons	Wairakau	Northland	Pyroxene andesite, rarer	Cone remnants in Sekeleton

Upper Miocene-Pliocene	Taranaki–Lower Wanganui	Henderson and Bartrum (1913, pp. 67–8, 73) thought these intermediate in age between Beesons Island and "Third Period" Volcanics	"Dacite Series"	Cape Colville Peninsula (Coromandel)	Dacite (Henderson and Bartrum, 1913)	Hotungaio cone in Residual Mountain Stage
Upper Miocene-Pliocene	Taranaki–Lower Wanganui	Correlation with above	Parahaki	Northland (Coromandel)	Dacite (Ferrar, 1925)	Cones in Residual Mountain Stage
Upper Miocene-Pliocene	Taranaki–Lower Wanganui	Solely on eroded cone form	Orangiwhao	South Auckland (Manukau) Taranaki	Hornblende Andesites (Henderson and Grange, 1926, p. 66)	Includes Whareorino and Pehimatea (Marwick, 1946, pp. 60–2). Cones in Residual Mountain Stage
Pliocene	Lower Wanganui	Pumice tuff at Whangamarino (Kear, 1957d, pp. 864, 867)	"Third Period"	Cape Colville Peninsula (Coromandel)	Pumice and rhoylite (Fraser and Adams, 1907)	Thought older than Rotorua-Taupo (Kear, 1957d, p. 867), but, in part, especially outlying islands, may be closer to Mayor Island and Pleistocene in age
Upper Pliocene	Waitotaran to Nukumaruan	Marine and plant fossils (Kear, 1957c)	Ngatutura	West Auckland (Auckland)	Camptonose basalt (Henderson and Grange, 1926, p. 71)	Skeleton Stage of erosion (on sea coast)
?Upper Pliocene to ?Lower Pleistocene	?Waitotaran–?Nukumaruan	Possibly erupted prior to formation of 550 ft terrace, broad correlation with Ngatutura Volcanics (Schofield, 1958b)	Bombay	Pukekohe–Bombay	Basalt (Schofield, 1958b)	Flows are well eroded and weathered
?Upper Pliocene to ?Lower Pleistocene	?Waitotaran–?Nukumaruan	Erupted subsequently to 900ft terrace level (Mason, 1953)	Horeke Flow	Hokianga (Auckland)	Basalt (Mason, 1953)	Age speculative
Upper Pliocene to middle Pleistocene	Waitotaran–?Castlecliffian	Volcanic products dated by paleobotany (Kear, 1957b, pp. 678–80); see also text of present paper	Basalts of Pirongia, Karioi, etc.	South Auckland (Auckland)	Olivine andesites and basalts (Henderson & Grange, 1926, pp. 67–9)	Cones at beginning of Residual Mountain Stage
Upper Pliocene to middle Pleistocene	Waitotaran–?Castlecliffian	Eroded forms of cones, and comparison with Pirongia, etc.	Younger andesites of Hauraki	South Auckland (Coromandel)	Pyroxene andesite (Bartrum, *in* Mead, 1938, pp. 495–6)	Cones (Te Miro Basin and Maungatautari) at beginning of Residual Mountain Stage. Placement in the Coromandel Andesite Province by present author

TABLE 1 *Continued.*

Age		Method of Dating	Volcanic Formation	Area and Volcanic Province (Grindley and Harrington, 1957)	Petrology	Remarks (Cone erosional stages as in Kear, 1957b)
European	New Zealand Series or Stage					
?Middle to Upper Pleistocene	?Castlecliffian to Hawera?	Eroded form and absence of 350 ft and higher terraces	Andesites of Little Barrier Island	Hauraki Gulf (Coromandel)	Hypersthene andesite (Bartrum *in* Hamilton, 1937, pp. 489–90)	Cone typical of Planeze Stage. High cliffed coast would not allow recognizable presence of terraces below 350 ft
?Middle to Upper Pleistocene	?Castlecliffian to Hawera?	Largely pre-dated 50 ft sea-level (Brothers, 1957, p. 558)	Rhyolite of Mayor Island	Bay of Plenty (Coromandel)	Rhyolites (Brothers, 1957)	Main cone post Planeze Stage (?older than upper Pleistocene), but central domes still within Planeze Stage
Middle to Upper Pleistocene	Hawera	Plant macrofossils at Kerikeri (Laing, 1954); post-dates 220 ft terrace at Kamo (Kear, in press)	Kerikeri	Northland (Auckland)	Basalt and andesite (Reed, 1948)	Would include earlier Taheke Flows (Mason, 1953, pp. 362–4)
Middle to Upper Pleistocene	Castlecliffian to Hawera	Plant macrofossils at Pokeno (Couper & McQueen, 1954); post-dates 110 ft terrace (Schofield, 1958b)	Franklin (Schofield, 1958b) Pakau (Gilbert, 1921)	South Auckland (Auckland)	Basalt (Henderson and Grange, 1926, pp. 69–70)	Cones in Planeze Stage
?Upper Pleistocene to ?Holocene	?Hawera to ?Holocene	Radiocarbon age (9150 ± 80 years B.P.; Fergusson and Rafter, 1955) of basalt flow at Penrose	Basalts of Auckland City	Auckland (Auckland)	Basalt (Reed, 1948)	Cones in Volcano to Planeze Stage
?Upper Pleistocene to ?Holocene	?Hawera to ?Holocene	Correlation with above on cone form, etc.	Younger basalts of Northland	Northland (Auckland)	Basalt (Reed, 1948)	Includes "Later Basic Volcanics" (Bell and Clarke, 1909), younger basalts of Kerikeri Series (Ferrar, 1925), "Recent Volcanic Rocks" (Ferrar, 1934), and the Third Taheke Flow (Mason, 1953)

minor amendment to the adopted range for the Skeleton Stage of cone erosion, and both should be borne in mind in future investigations.

Sequence of Volcanism and Tectonic Activity

Figure 1 illustrates clearly that the sequence of volcanism has tended to be andesite (oldest), dacite, rhyolite, and basalt (youngest). The upper Tertiary Kaikoura Orogeny was undoubtedly later than the Waitemata and Manukau andesites, since both formations were involved in tectonic movements of that orogeny; and it was undoubtedly earlier than the Waitotaran (upper Pliocene) and younger basalts, since the orogeny occurred prior to the deposition of the Opoitian (lower Pliocene) Kaawa Shellbed (Marwick, 1948; Kear, 1957c; Schofield, 1958a). The Kaikoura Orogeny may thus be placed as later than most, if not all, andesites, and earlier than all basalts.

These broad conclusions agree with sequences that have been worked out locally both within New Zealand and overseas. Ferrar (1934, pp. 54–60) gave the "post-Eocene" volcanic sequence in Northland as: andesite (oldest), dacite, rhyolite, and basalt (youngest). He considered (p. 58) that the dacites and rhyolites post-dated the block-faulting at Waipu; and Kear (1959) placed the faulting at Kamo, 30 miles north of Waipu, as post-dacite and pre-basalt. Henderson and Bartrum (1913, pp. 51–2) recorded the volcanic sequence in the Aroha Subdivision (Cape Colville Peninsula) as andesite (oldest), dacite, and rhyolite (youngest), with post-dacite and intra-rhyolite faulting. Horberg, Edmund, and Frexell's (1955) sequence of tectonics and volcanism in Wyoming was: andesite (oldest), faulting, rhyolite, basalt (youngest). Spurr (1905) recorded andesite (oldest) rhyolite, and dacite, uplift, and basalt (youngest) at Tonopah (Nevada).

There appears, then, to be a fundamental volcanic sequence of andesite (oldest), dacite, rhyolite, and basalt (youngest); with tectonic activity probably post-andesite, and certainly pre-basalt (i.e., occurring slightly before, slightly after, or during the eruptions of rhyolite and dacite). Any post-basalt faulting should be minor, and consequent upon volcanism (e.g., caused by post-eruption collapse; see also Schofield, 1958b, p. 550). This simple sequence might presumably become more complex because of magmatic differentiation, assimilation, or rejuvenation of volcanism.

The facts that the andesites, dacites, and rhyolites tend to be distributed in arcuate form, whilst the basalts do not, and that the arcuate form is shared also by the pre-Tertiary basement main trend of the island (Macpherson, 1946, map 2), suggest that the dacites and rhyolites are tectonically more akin to the andesites than to the basalts, and that their distribution is related more to pre-Tertiary (Hokonui Orogeny) than to late-Tertiary (Kaikoura Orogeny) structure. It appears likely, therefore, that eruption of rhyolite was no later than the end of the Kaikoura Orogeny. The basalts were erupted up fault-planes of block faults that were the product of the typical block-faulting of the Kaikoura Orogeny in Northland and South Auckland.

Application of Time Sequence to Volcanic Belt

Broad application of the above fundamental time sequence to the Volcanic Belt leads to an interesting conclusion. There is an understandable tendency to consider andesitic eruptions as a late phase of New Zealand volcanism because the active volcanoes at Tongariro National Park are andesitic. However, their present activity can be explained alternatively by a southward shifting focus of eruption that reached the Tongariro National Park area in late geological times. Locally in that area, the normal sequence would have begun with andesite (no older rhyolitic rocks are inferred—Fleming and Steiner, 1951), and would not as yet have reached any of the later stages. Some of the sequences to the north-east, that appear anomalous in having ignimbrite below andesite, might be explicable either in terms of differentiation, assimilation, or rejuvenation, or in terms of considerable southward movement of ignimbrite from a more northerly, and therefore possibly older, source.

Other speculative inferences are possible: that the dacitic and rhyolitic phases of the sequence may yet reach the Tongariro National Park area; and that the Kaikoura Orogeny may be considered to be unfinished as yet in at least the southern part of the Volcanic Belt, where andesite eruptions are taking place at Tongariro National Park and where rhyolitic pumice was erupted at Taupo during the Holocene (Baumgart, 1954).

The elucidation of such points as these, and the explanation of the apparently anomalous position of the present-day activity at White Island (which might possibly be connected with eastward movement of Coromandel andesitic arcs) must await more accurate and numerous datings from within the Volcanic Belt itself.

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THE ALPINE FAULT FROM LAKE McKERROW TO MILFORD SOUND

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Summary

The Alpine Fault intersects the west coast of the South Island of New Zealand about four miles north of Dale Point at the entrance to Milford Sound; moraine on the west of the fault has been faulted against Fiordland Gneiss on the east. A well defined fault trace was followed from the air from the south side of Lake McKerrow through the east side of a huge eroded crush zone in the Kaipo River to the contact between moraine and gneiss at Stripe Point. The fault trace interrupts topography that probably formed during the last glaciation. The major displacement is dextral transcurrent and similar in direction and amount to that on the fault in the north, the valley of Kaipo River being displaced about a mile. The Alpine Fault is thus a major transcurrent fault at its southern limit on land with essentially the same character as along the western side of the Alps to the north.

INTRODUCTION

The major importance of the Alpine Fault in its central part is now generally accepted (N.Z. Geological Survey, 1958) but different interpretations have been given to explain its relations to the major structure of the South Island. The inferred positions of the northern and southern extensions of the fault have depended largely on the structural interpretation adopted. Macpherson (1946) followed Benson (1926) and considered that the New Zealand ultra-basic rocks had been intruded along major thrust faults. Macpherson's Map 1 shows a line of major thrusts to the west of the ultra-basic belt from D'Urville Island to Top House, along the line of the Alpine Fault to near Jackson's Bay, and then south and south-east along the line of the ultra-basic and basic intrusives from western Otago to the east coast near Milton. The southern end of the Alpine Fault was shown as a questioned dotted line. Lillie (1951, p. 228) has clearly explained why Macpherson's thrusts do not agree with what is known of the Alpine Fault. After quoting Macpherson (1946, footnote page 11) he states "We now have a picture of great thrusts, . . . , and even a foreland obstacle. But in this connection there is one irreconcilable feature: the Alpine Fault has been mapped in many places, often with high country situated on each side of it, and its trace appears to be remarkably straight. There are none of the sinuosities we might expect on the margin of a thrust plane and no klippes. All the available evidence suggests that the Alpine Fault in so far as concerns its present surface trace is not a thrust according to the Alpine worker's usage; it cannot

N.Z. J. Geol. Geophys. 2 : 590-601.

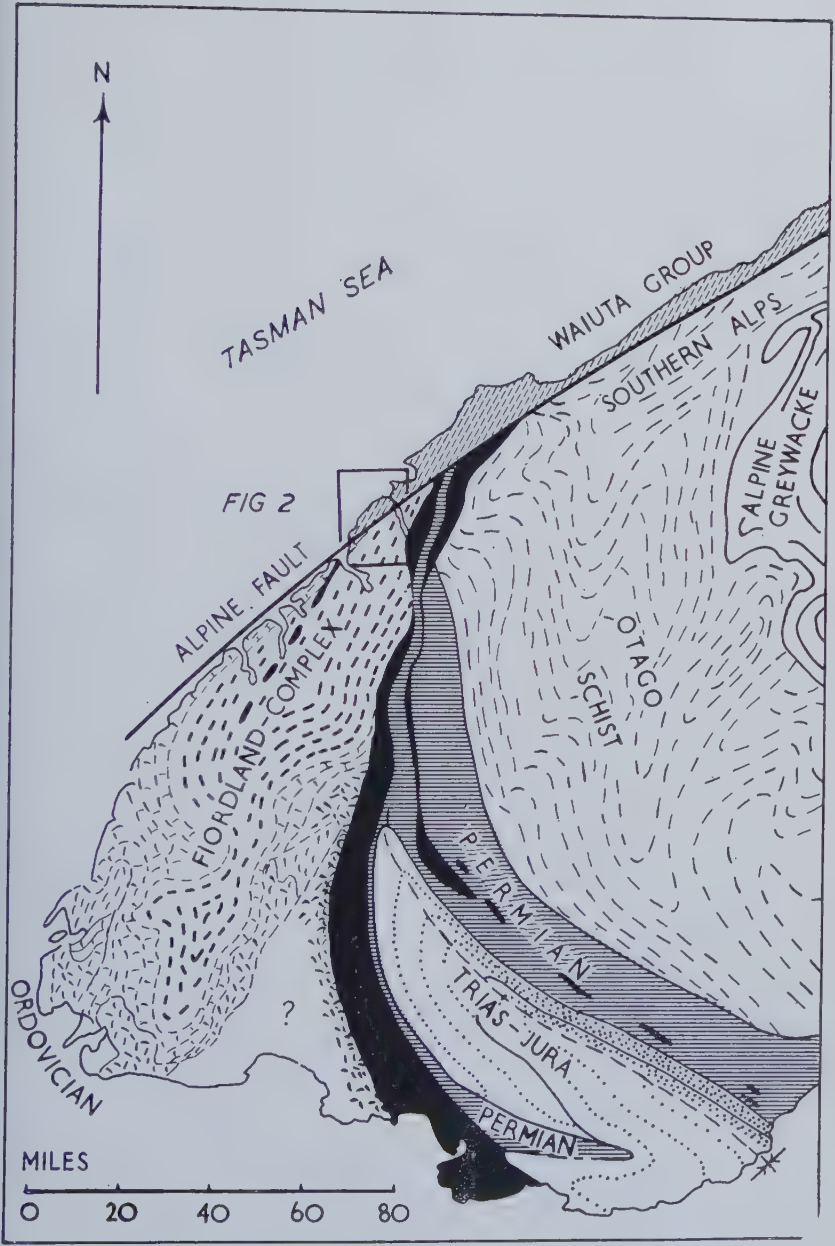

FIG. 1.—Locality map showing relation of Alpine Fault to major structure of South Island. Based on New Zealand Geological Survey 1958 Geological Map. Permian igneous rocks in black, calc-silicates in Fiordland Complex in "limestone" symbol. Post Cretaceous rocks omitted.

be compared with the Moine Thrust. The great thrust of Otago, postulated by Macpherson, seems to have passed into a reverse fault, in places remarkably near vertical, and of prodigious throw. The possibility of the Southern Alps being formed by a great overthrust cannot be ruled out entirely if such were imagined to have occurred in early or middle Tertiary time. One can conceive of later vertical faulting superimposed over an old thrust pattern and followed by erosion, but evidence to support such a view is insufficient. Indeed, the available evidence is against direct comparisons with Alpine tectonic patterns."

Wellman (1953) showed that Pleistocene and Recent movement on South Island faults was essentially dextral transcurrent, and he suggested (Wellman, 1956) that the pre-Cretaceous rocks of the South Island had been displaced by a 300 mile dextral shift along the Alpine Fault and its continuation, the Wairau Fault. This interpretation was based on the apparent match between the belts of rocks that are cut off to the south-east by the Wairau Fault at the north end of the South Island and those that are cut off to the north-west by the Alpine Fault at the south end of the island. The Alpine Fault was inferred to continue south-west from Lake McKerrow along the northern Fiordland Coast (see also Grindley, 1958). The pre-Cretaceous rock belts and the faults are clearly shown on the 1958 Geological Map of New Zealand.

Kingma (1959) discussed the structure of the South Island and put forward a structural interpretation that in part is intermediate between those of Macpherson and Wellman. He accepted several miles of dextral transcurrent movement at the north end of the island but adopted the Otago thrust from Macpherson at the south end. The south-west extension of the Alpine Fault was shown as a dotted line on his fig. 2 and not shown at all on his fig. 9.

The test of a structural interpretation lies in the number of features that it can forecast in regions that have not been examined. Macpherson and Kingma were uncertain if a major fault exists from Lake McKerrow to the Fiordland Coast, but a major fault in this position must be inferred from the theory of the 300 mile displacement. The area between Lake McKerrow and Milford Sound (Figs 1 and 2) is thus a critical one at the present state of tectonic interpretation.

COASTAL OUTCROPS AND OBSERVATIONS FROM AIR

The writers spent four days in the field and also examined the area from the air. Ground examination was confined to the east side of the entrance to Milford Sound between Dale Point and Yates Point. The main features of the geology are shown by Fig. 3. Two main rock types are represented: Fiordland Complex on the east side, and moraine on the west side of the fault. The Fiordland Complex consists of strongly foliated gneiss that contains bands of calc-silicates in the neighbourhood of Stripe Point. The bands of calc-silicates range up to 10 ft in thickness and are mostly strongly contorted, being similar to the calc-silicate bands illustrated by Benson (1933, Pl. 42B).

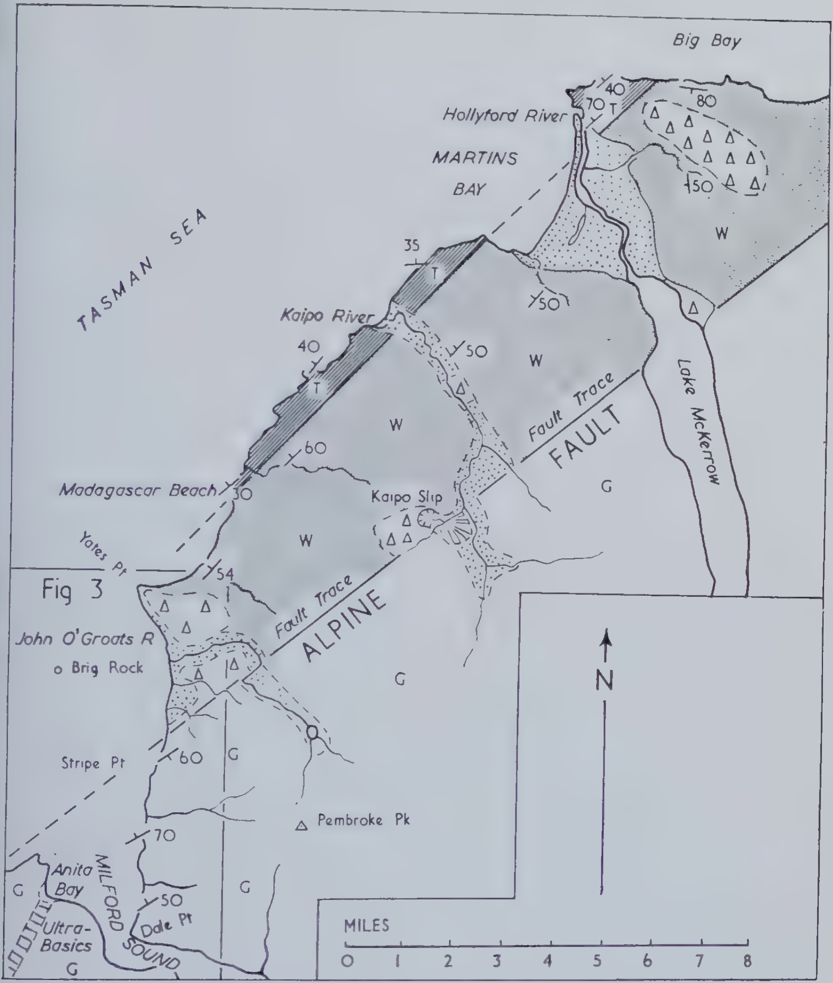

FIG. 2.—Sketch map showing Alpine Fault from Lake McKerrow to Milford Sound. Geology and topography based on Healy (1938) with additions sketched from air photos. Alluvium, dots; Piedmont Moraine, triangles; Tertiary, T.; Fiordland Gneiss, G; Waiuta Group, W.

The calcareous and other well defined bands show that the gneiss was originally a sediment; cross-bedding, seen in a few loose blocks one mile south of Stripe Point, prove a sedimentary origin, but it is not sufficiently well exposed in place to allow the order of superposition to be determined readily.

Although the gneiss is strongly contorted, the regional strike is fairly regular at about 040°. The dip is less regular but at most places exceeds 45°. The contortions show that the structure is complex in

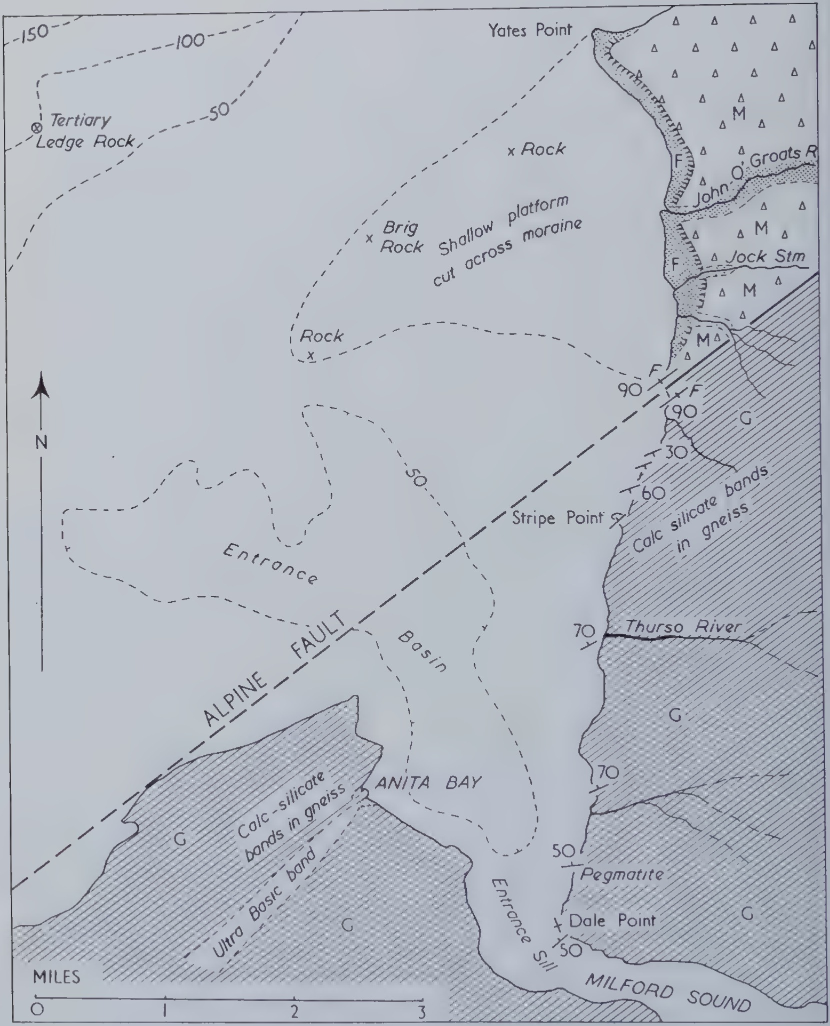

FIG. 3.—Detail map from air photos showing relation of Alpine Fault to outcrops on coast north of entrance to Milford Sound. Post-Glacial Beach deposits, F; Piedmont Moraine, M; Fiordland Gneiss, G.

detail, but the presence of mappable belts with distinctive lithology suggests that large scale structure may be less complex than it would appear to be at first sight. Only one important fault was seen within the Fiordland Complex. It is a mile north of Stripe Point, strikes at 040°, dips vertically, and contains about a foot of soft fault pug. Striations on the north side of the fault are horizontal and indicate transcurrent movement, but the sense of the movement is uncertain. Between the fault and Stripe Point the gneiss is slightly less massive than to the south. The most northerly gneiss outcrop is pulverized and poorly exposed beneath thick scree. The first outcrop of moraine on the coast is about 100 ft north of the pulverized gneiss, the rocks between being obscured by scree. The moraine is composed of well rounded fragments of gneiss set in a tight clay matrix. About 200 ft north a minor fault, parallel to the fault in the gneiss, cuts the moraine, but the direction of throw could not be determined. The two parallel faults and the sudden disappearance of the gneiss which rises several hundred feet above sea-level immediately to the south-east is consistent with the view that the junction between the moraine and the gneiss is a fault contact. From a mile to the west it could be seen that a well defined continuous trench partly occupied by streams lies along the line of the fault. The most westerly stream was traversed up to the gneiss. At the line of the trench about 100 ft of pulverized gneiss is exposed in a 60 ft slip. Moraine outcrops at river level 50 ft downstream but the actual contact was not seen. The moraine does not appear to contain any fragments of the pulverized gneiss and the relative position of the outcrops is evidence that the contact is a fault. The fault trench shows on air photographs, strikes at 045°, and is parallel to the faults observed in the gneiss and moraine.

Unusual pebbles and boulders were found at the mouth of Jock Stream between the Alpine Fault and John o' Groats River. The most common are pebbles of dark flinty graphitic argillite similar to some of the lower Paleozoic rocks of Preservation Inlet and North-West Nelson and different from upper Paleozoic argillites of the Eglinton Valley-Hollyford River belt. Less common are boulders of brecciated limestone that are much lower in rank than the marbles interbedded with gneiss at Milford Sound. These rock types were not seen elsewhere and may be derived from an infaulted strip between the gneiss and the moraine in the middle reaches of the stream.

Conclusive evidence for the fault was seen from the air. A flight was made from the head of Milford Sound to Yates Point, along the coast to Martins Bay, then east to the most southerly previously determined position of the fault on the south side of Lake McKerrow (Wellman and Willett, 1942b: 289), and then along the line of the fault to the contact at the coast just described. A continuous fault scarp extends from the notch in the hills on the south side of the lake to the north side of Kaipo Valley. The direction of throw is uncertain from the air but appears to be up on the eastern side when viewed from the opposite side of the lake (Wellman and Willett, 1942a: 289). The floor of Kaipo Valley is covered by a massive fan derived from a huge crush zone with steep shear planes on the south side of the valley (Fig. 4), and the fault scarp does not show in the valley floor. It reappears on the south side of the valley east of the crush zone and is continuous and uniform for 5 miles to the valley of John o' Groats River. The throw is up on the west side, the amount of throw being about 50 ft. John o' Groats River has been dammed and diverted north by the fault, a swamp being formed on the upstream side of the fault (Fig. 5). From John o' Groats River to the coast the

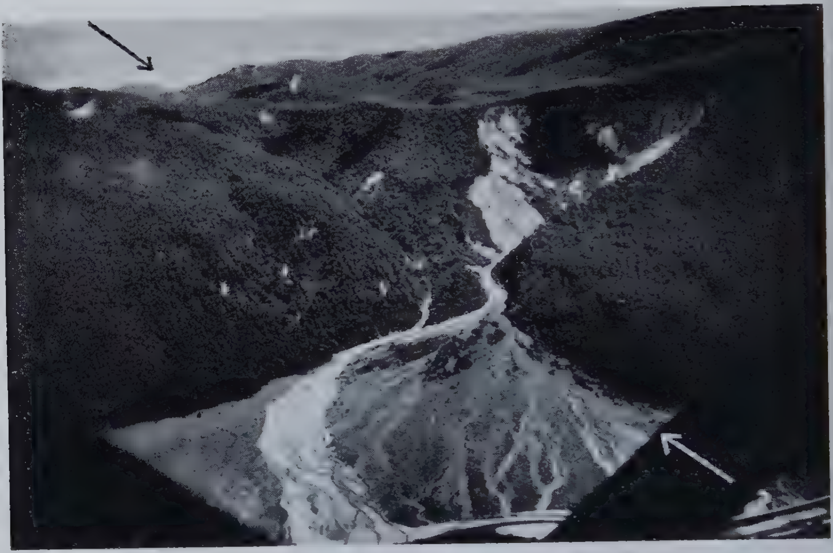

FIG. 4.—View west of erosion-scar and debris fan Kaipo River. The gulch, about 1,000 ft high, is eroded in rocks pulverized by the Alpine Fault. Steep shear planes parallel to the fault show at back of gulch. Moraine about 50 ft thick shows as a dark band at the top of the gulch. Position of Alpine Fault indicated by arrows.

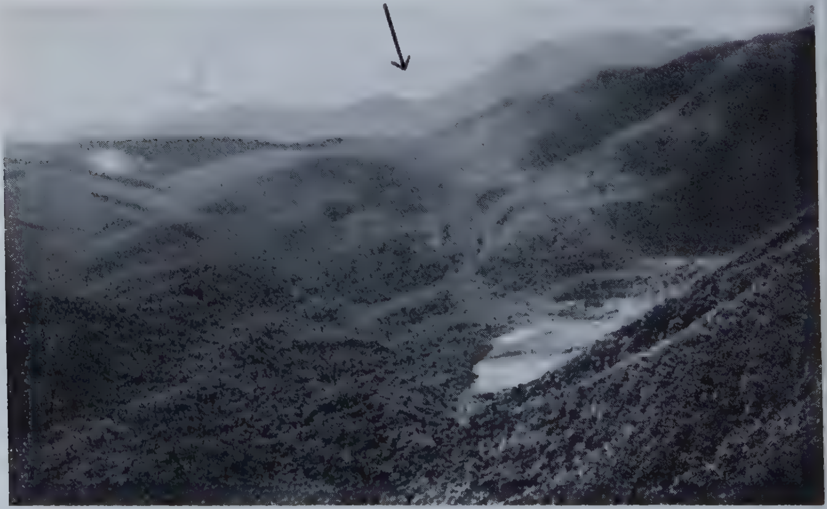

FIG. 5.—View north-east along Alpine Fault from above coast. The recently upthrown western block has dammed John o' Groats River (right foreground) to create a swamp. The fault trace, indicated by an arrow, shows on the divides as far as the north side of Kaipo River.

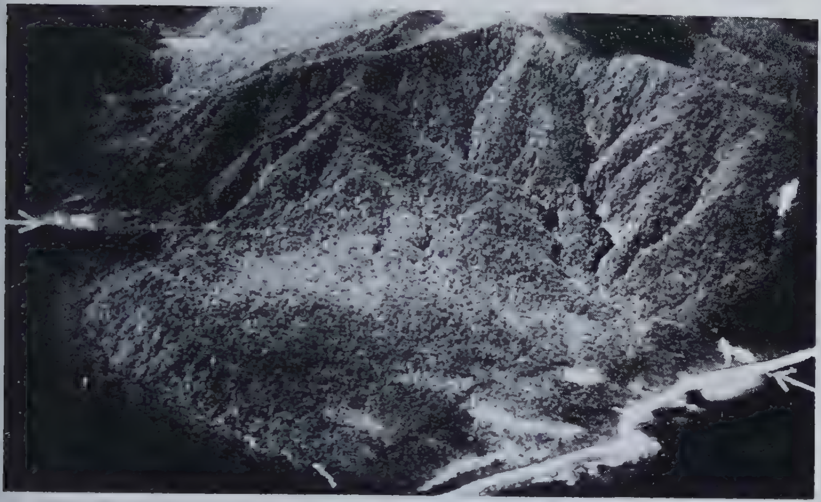

FIG. 6.—View south-east across Alpine Fault between swamp in John o' Groats River (left) and the sea (right). Scarp behind the fault is Fiordland Gneiss, foreground moraine.

line of the fault is crossed by two streams, the more southerly being the one traversed from the coast. The fault, although not so well defined or regular as in the north, could be clearly traced to the coast and forms the trench between the moraine and the gneiss already described (Fig. 6).

GLACIATION AND GLACIAL DEPOSITS

Some knowledge of the different periods of glaciation and of their probable dates is essential for an understanding of the rate of movement on the fault. Glaciation in the Milford Sound area is similar to that to the south and north already described by Benson, Bartrum, and King (1934) and by Wellman and Willett (1942b). Two distinct periods of glaciation are represented: a late one by the glacial topography within Milford Sound and an early one by the Piedmont Moraine to the east of the Alpine Fault. The glaciation within Milford Sound has been described by Brunn *et al.* (1955). Glacial features are sharp and about half the rock below the inferred upper limit of glacier ice exhibits glacial smoothing and grooving. The steeper parts of the ice-smoothed rock have fallen away to form cliffs that are most clearly displayed on the south side of Milford Sound. These rock-fall-cliffs are illustrated by Brunn *et al.* (1955, figs 1 and 2) but were interpreted by them as "fresh cutting". They are not grooved, have blocky fractures, and are clearly post-glacial. As might be expected, rock falls increase inland where the climate is more extreme than on the coast and at Homer Tunnel 15 miles inland very little ice-smoothed rock has escaped rock-fall erosion.

The glacial features of Milford Sound are so fresh that they must represent the last major glacial advance and are unlikely to be more than 20,000 years old. Fresh glacial features end at Dale Point. The topography beyond was probably caused by glacial action, but it has been so strongly modified by stream and wave erosion that no conclusive topographic evidence for glaciation remains. The "entrance sill" just inside Dale Point (Fig. 3) described by Brunn *et al.* (1955, 402) is doubtless the terminal moraine of this last major ice advance.

West of the Alpine Fault glacial history has to be inferred from moraine and not from erosional features. Moraine forms a flat topped ridge that extends out to Yates Point (Fig. 7) and down for an unknown depth below sea-level. It is similar to the Piedmont Moraine of South Westland (Wellman and Willett, 1924b; Wellman, 1955) and to the moraine capping the Coastal Plateau in southern Fiordland (Benson, Bartrum, and King, 1934).

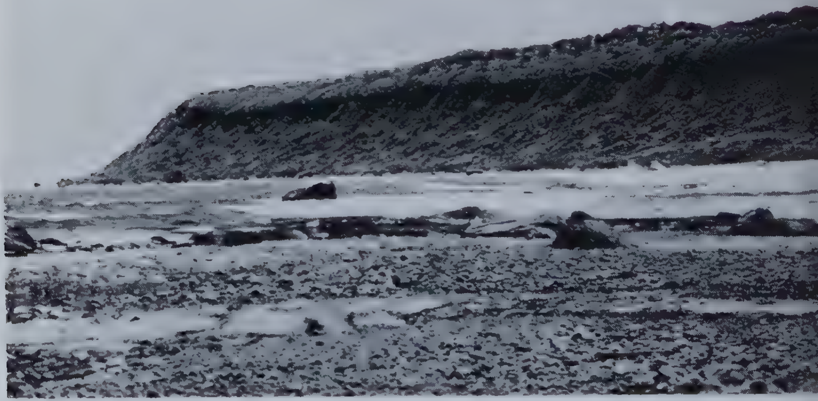

FIG. 7.—View of Yates Point from mouth of John o' Groats River. Steepest pa of the cliff is moraine underlain by varved silts. Gentler slope at base is scre

The moraine cliff that extends east from Yates Point to the valle of John o' Groats River has a remarkably uniform profile for i whole length, being steep at the top and much flatter below (Fig. 7 In a stream section about a mile east of Yates Point, the steep scar at the top is composed of moraine with boulders of gneiss up to 10 across. The break in slope coincides with the top of a 20 ft band varved silt which overlies moraine similar to that above the silt. Tl gentle slope below the silt is scree. The uniformity of the cliff profi for its whole length makes it likely that the varved silt is continuo for the whole length of the cliff, and that this moraine section more uniform than those to the north (Wellman and Willett, 1942b

This is possibly due to the cliff being parallel to the probable flow of the glaciers and not at right-angles to the flow as are most of the northern sections. The silt is evenly bedded and appears to dip west at a few degrees. It probably accumulated in a fresh-water lake contained to the south by a morainic barrier that has since been eroded. The cliff itself was probably cut by the sea, and is now flanked by recent gravels that rise to about 10 ft above mean high water mark, and are about 500 ft wide at John o' Groats Valley.

Nowhere along the coast can the Piedmont Moraine be attributed to any particular valley glacier and at several places the Piedmont Moraine was deeply trenched by rivers that flowed from valley glaciers of the last main advance. The Piedmont Moraine is thus older than the last glacial advance. On the other hand in spite of the high rainfall and temperate climate weathering is not deep. At the surface of the moraine coarse grained igneous boulders have a weathered skin about an inch thick but quartzose greywacke is not appreciably affected. By comparison with overseas moraines the Piedmont Moraine belongs to the last and not to the penultimate glaciation. It would thus seem to represent the earliest phase in the last glaciation with an age of about 150,000 years, considerably younger than suggested by Wellman (1955, p. 39).

The oldest topographic features displaced by the Alpine Fault cannot be older than the Piedmont Moraine and are either the same age as the upper deposits or more probably younger and in part intermediate in age between the Piedmont Moraine and the last major advance and partly the same age as the last major advance. The river valleys that are displaced a mile are considered to be intermediate in age, and the surface that is displaced 50 ft may be the same age as the last major advance.

CONCLUSIONS

The Alpine Fault extends as a major active fracture along the western side of the Southern Alps and the northern Fiordland Mountains to reach the coast near Stripe Point. The position of the fault and the major displacements that have been determined north of Lake McKerrow are listed by Wellman (1953). The most significant displacements in the southern part of the fault are probably the 1,000 ft horizontal shift of glaciated surfaces on the south bank of Martyr River (Wellman, 1953, p. 280), which probably represents the horizontal shift since the last major glacial advance, and the shift of about a mile of the major streams which is fairly uniform for the whole length of the fault. A horizontal shift of about a mile is also shown by the Kaipo River. As already mentioned, the major rivers at the fault are probably older than the last major glacial advance and younger than the Piedmont Moraine, and probably some five times as old as the last main glacial advance. If the age of the last glacial advance is taken as 20,000 years, then the annual rate of movement as determined from the 1,000 ft displacement at Martyr

River is about half an inch per year. The available evidence suggest that the rate of movement has been about the same since the formation of the main rivers and as there is no evidence for an increase i tectonic rates since the early Pleistocene a ten mile shift would b likely since the beginning of the Pleistocene. Extrapolation into th Tertiary is uncertain but it should be noted that the postulated 300 mil shift could have been accomplished since the Oligocene if movemen had been at the same rate as at present.

North of Lake McKerrow the eastern side of the fault has bee upthrown relative to the western side. The amount of vertical displacement is more variable than the horizontal shift and appears to depen on the position as well as on the age of the displaced feature, th rate of uplift being most rapid opposite the high mountains of th Southern Alps. An upward movement of the gneiss on the east sid of the fault relative to the Piedmont Moraine is strongly suggested b the section at Stripe Point, the suggested amount of movement bein possibly at least 1,000 ft. The recent upward movement on the west sid of the fault indicated by the displaced surface topography south o Kaipo River can be matched to the north by the upward displacemen of the west side of the Wairau Fault towards its northern extremit (Wellman, 1953, p. 282). The fault near West Cape in Fiordland i also upthrown on the western side (Wellman, 1953: 288). The fault that are upthrown on the west are at the two extremities of the Sout Island and may lie to the east of the present axis of uplift.

Although the Alpine Fault has been proved to extend to Milfor Sound as a major active feature, in the position previously mapped b extrapolation, the relation of the fault to the old rocks has not bee conclusively determined. Gneiss of the Fiordland Complex extend west to the fault at Stripe Point and probably continues along th east side of the fault to outcrops on the north side of Lake McKerrow Healy (1938) mapped schist (Waiuta Group, figs 1 and 2) thre miles west of the fault and it is extremely likely that the schist (wit possible intrusions of granite) will extend to the fault. The schist an granite cannot be confused with any rocks of the Fiordland Comple

The crush zone at Kaipo Valley is the best evidence for a majo displacement of the undermass. The crush zone is about half a mil wide and similar to the crush zone at the Alpine Fault at Waitah Valley described by Morgan (1908, p. 66) as one of the large in New Zealand.

All available evidence indicates that the Alpine Fault continues without significant change in character from South Westland to the Fiordland coast.

ACKNOWLEDGEMENTS

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GEOCHEMICAL PROSPECTING FOR URANIUM IN THE LOWER BULLER GORGE, NEW ZEALAND

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Summary

One hundred and fifty-six water samples from 17 localities in the Lower Bulle Gorge were analysed for uranium.

The uranium content of surface waters was found to vary significantly wit weather conditions, the peak uranium concentration occurring shortly after th onset of heavy rain following a dry period.

The method appears to be applicable for the identification of discrete areas tha are comparatively rich in overall uranium content. Detection of localized concen trations of uranium is dependent on the presence of a small stream draining th critical area.

The method has little practical application in the Lower Buller Gorge are where prospecting with a scintillometer is much simpler and more effective.

Introduction

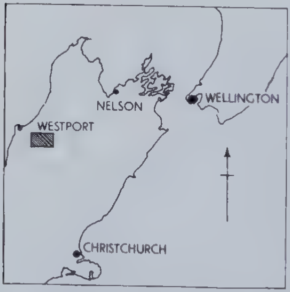

Fig. 1.—Map showing location of Buller Gorge area.

Geochemical prospecting for uraniu minerals in the Lower Buller Gorge are South Island New Zealand (Fig. 1), ha been based on the technique described b Ostle (1954). The work was undertaken t assess the value of the method in this loca ity and to determine the effect of weathe conditions on the concentration of uraniu in surface waters. Work was carried out i the Lower Buller Gorge because of th known occurrence of uranium in the are

Geology

The geology of the Lower Buller Gorge has been described b Morgan and Bartrum (1915), Wellman (1950), Beck, Reed, and Wi lett (1958), and is shown on the accompanying maps (Figs 2 and 3 A brief outline of the geology is given below.

Basement rocks include Paparoa granite-gneiss, Greenland Seri sediments, and quartz-porphyry intrusives.

The Paparoa granite-gneiss varies in composition from granitic granodioritic. Gneissic banding is common and in some localities th

N.Z. J. Geol. Geophys. 2 : 602-12.

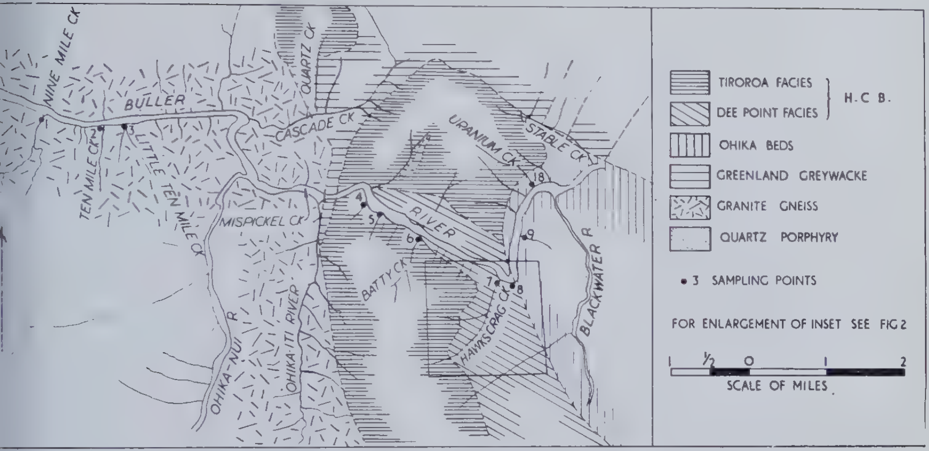

FIG. 2.—Geological map of Lower Buller Gorge.

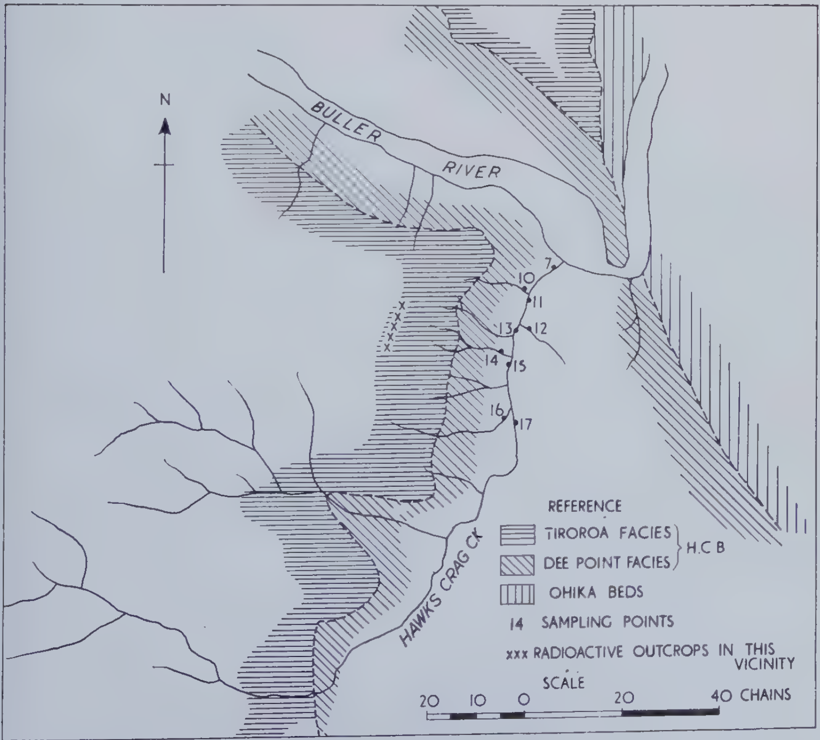

FIG. 3.—Geological map of Hawks Crag Creek catchment area (enlargement of inset in Fig. 2).

gneiss is porphyritic. Weak uranium mineralization has been found associated with a quartz-purple fluorite-barite lode, and in a pyritized crush zone. Both occurrences are in Mispickel Creek (Fig. 2). A few pegmatite dykes, and some biotite-rich bands in the gneiss are slightly radioactive. Background counts are, in general, higher than in other basement formations.

Greenland Series consist of well indurated phyllitic greywackes of Paleozoic age. A weakly radioactive pyrite-molybdenite-chalcopyrite lode occurs in Quartz Creek (Fig. 2).

Ohika beds, of Upper Jurassic age, rest unconformably on the basement rocks and consist of non-marine shales, tuffs, sandstones, and conglomerates. No uranium occurrences are known in the Ohika beds, and the background counts are generally low.

The Hawks Crag Breccia (Middle to Upper Cretaceous) rests unconformably on the Ohika beds. Following recent work (Beck *et al.*, 1958), the Hawks Crag Breccia has been divided into three facies:

(i) Tiroroa facies consisting of rounded to sub-rounded granite pebbles and boulders, which are set in a coarse, angular, arkosic matrix.

(ii) Dee Point facies consisting of angular to sub-angular greywacke fragments set in a silty matrix.

(iii) Blackwater facies (not present on area covered by Fig. 2) consisting of granite and greywacke pebbles and boulders set in a silty matrix.

The greater part of the uranium in the Lower Buller Gorge occurs in bedded deposits in the Tiroroa facies. The predominant uranium mineral is coffinite, which is found associated with calcite (up to 10%) and lesser amounts of pyrite and fluorite. Background counts in the Tiroroa facies are high, while in both the Dee Point and Blackwater facies the counts are low.

CLIMATE, VEGETATION, AND TOPOGRAPHY

The most striking feature of the climate in the Lower Buller Gorge is the heavy rainfall. Near the coast the average annual rainfall is 80 in., and 15 miles inland it approaches 200 in. per annum. Periods of up to one month occur when little or no rain falls. The climate is temperate, average winter and summer temperatures not varying by more than 15° F.

Below 3,500 ft, the area is covered with dense beech forest.

The streams are short and their profiles are steep. The relief varies between 2,000 ft and 4,000 ft, the country being rugged and difficult to traverse. The steepness of the country precludes the accumulation of products of weathering except at the foot of bluffs and in river valleys. Excluding the Ohika beds, which are well jointed, the rocks are massive, and weathering extends only a short distance below the surface.

METHOD

Field Procedure

One hundred and fifty-six water samples were collected from 17 localities. Localities 1 to 9 are in creeks draining granite-gneiss, Tiriroa facies of Hawks Crag Breccia, Dee Point facies of Hawks Crag Breccia, and Ohika beds. The samples were collected and analysed and the results correlated with changes in weather and variation in rock type. Sampling localities 10 to 17 are in the vicinity of uraniferous horizons and the samples were collected and analysed to assess the value of the method in prospecting for uranium deposits.

The flow of water in Batty Creek (Fig. 2) was measured every time a batch of samples was taken from localities 1 to 9. This was used as a rough measure of weather conditions prior to taking the samples. All samples were collected in 500 ml polythene bottles.

Laboratory Procedure

The laboratory procedure is that described by Ostle (1954). The sample is passed through a column of anion exchange resin, the resin is burnt on a platinum dish, and the products are fused with a flux. The fluorescence of the resultant phosphor is compared with standard phosphors under an ultra violet lamp.

Because of the low concentration of uranium in surface waters draining into the Buller River, it was found that greater accuracy was obtained using 200 ml of water for each analysis, instead of the 100 ml recommended by Ostle (1954). It was also found that a very important factor affecting the accuracy of the analysis is the temperature at which fluxing is carried out. The temperature should be kept as close as possible to the melting-point to avoid excessive quenching.

RESULTS

Tables 1 and 2 show the uranium content of water from sampling points 1 to 9 and 10 to 17, and the weather conditions prior to sampling. The average uranium concentration and the rock type present in the catchment area are shown in Table 3. Wherever a full set of samples was not collected, the averages were weighted by comparison with fully sampled creeks. The average uranium content of the water at sampling point 18 was calculated from four samples collected and analysed by Mr K. E. Beer, of the Geological Survey of Great Britain. The results from Table 1 were used to calculate the average uranium content of creeks draining Paparoa granite-gneiss, Tiroroa facies, Dee Point facies, and Ohika beds, shown in Table 4. In Fig. 4, the uranium content of water at six sampling points is plotted against weather conditions.

TABLE 1.—Uranium Content of Water from Sampling Localities 1 to 9, Taken Under Varying Weather Conditions.

	Sampling localities										
	1	2	3	4	5	6	7	8	9	Flow in Batty Creek (cusec)	Remarks
Grid ref. S 31/	148631	161628	166629	220611	223608	233604	251593	255593	257605		
μg U_3O_8/litre	0·96	1·0	0·84	0·52	0·69	0·42	0·39	—	—	8·0	Samples collected after prolonged heavy rain. Values recorded are averages of 4 sets of samples.
	0·75	0·72	0·85	0·55	0·4	0·15	0·24	—	—	4·0	Heavy rain followed by 3 days of fine weather. Values recorded are averages of 2 sets of samples.
	0·45	0·4	0·7	0·7	0·45	0·55	0·35	—	—	1·3	Samples taken after one month drought.
	1·25	1·25	1·25	1·25	1·05	0·8	0·85	0·4	—	3·5	One month drought followed by 12 hours rain.
	3·3	2·5	3·25	3·25	2·3	1·4	1·45	—	0·65	5·5	One month drought followed by 24 hours rain.
	1·45	—	—	—	1·25	—	—	—	—	5·5	One month drought followed by 2 days rain.
	0·6	—	—	—	0·6	—	—	—	—	14·5	One month drought followed by 4 days rain.
	0·75	0·9	0·85	0·8	0·35	0·3	0·2	—	0·3	5·5	One month drought followed by 6 days rain.
	0·45	—	—	—	0·4	—	—	—	—	3·0	Heavy rain followed by 3 days fine weather.
	0·32	0·27	0·55	0·45	0·45	0·55	0·32	—	—	1·7	Heavy rain followed by 9 days fine weather.
	3·0	3·0	1·55	1·05	1·35	1·3	1·25	—	—	3·5	10 days drought followed by 12 hours heavy rain.
	1·15	1·0	1·65	0·67	1·5	1·45	0·35	—	—	1·8	Three weeks drought followed by 12 hours intermittent rain.
	3·0	1·35	1·35	1·15	1·35	1·0	0·95	0·6	—	2·0	Three and a half weeks drought followed by 24 hours intermittent rain.

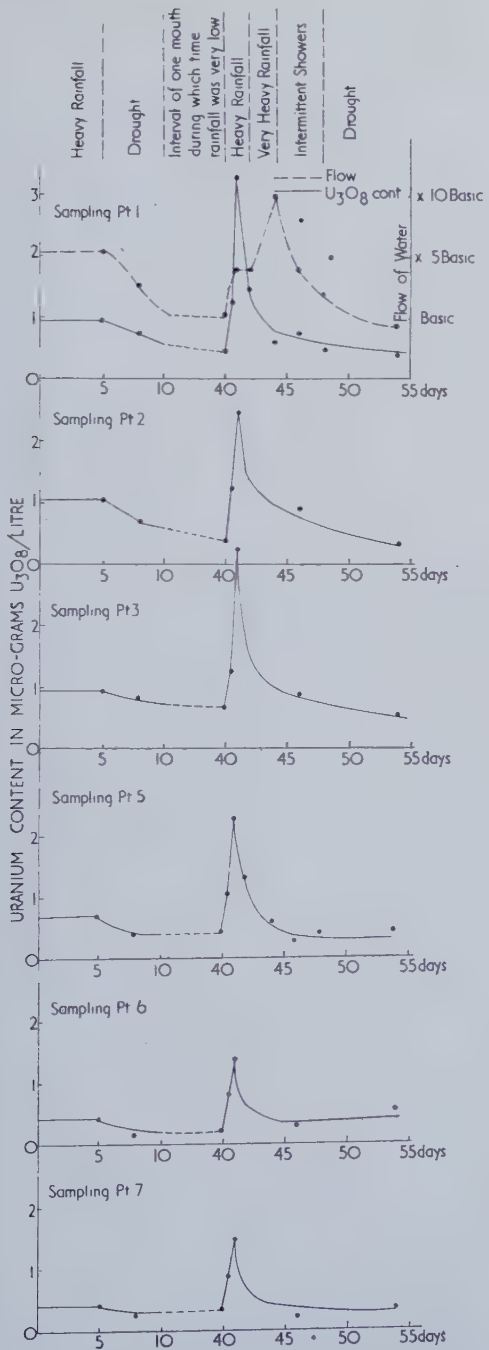

FIG. 4.—Graphs showing variation of uranium content in stream water during changing weather conditions.

THE EFFECT OF WEATHER ON THE URANIUM CONTENT OF SURFACE WATERS

From the graphs shown in Fig. 4, it is seen that the uranium content of surface waters varies markedly with changes in weather, thus precluding direct correlation of results from creeks sampled under different weather conditions. The similarity with which uranium concentration varies in different creeks, however, suggests a method by which approximate correlation can be made. At the start of a geochemical prospecting programme, a creek is chosen, the uranium content of which is determined under all weather conditions. This "standard" creek is resampled every time a batch of samples is collected. It is then determined whether the result from the "standard" creek is high, low, or average, and the results from other creeks are weighted accordingly.

Figure 4 shows that the uranium content of the creeks sampled was highest during the first 36 hours of rainfall following a period of drought.* The desirable time for collecting water samples is when the peak value occurs, as it is then that the differences in uranium concentration become most pronounced. It is dif-

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*"Drought" identifies a period during which only slight rainfall occurred, causing negligible increase in stream flow.

TABLE 2.—Uranium Content of Water from Sampling Localities 10 to 17.

	Sampling locations								
	10	11	12	13	14	15	16	17	
Grid ref. S 31/	250591	250591	250590	250590	249589	249589	249586	249586	Remarks
μg U_3O_8/litre	0·5	0·15	0·2	0·15	0·3	0·25	0·45	0·15	Rain followed by 10 days drought.
	1·25	0·75	0·3	0·75	1·4	0·65	1·45	0·55	Ten days drought followed by 12 hours rain.
	0·9	0·8	0·7	0·6	1·0	0·75	1·1	0·65	Ten days drought followed by 3 days rain.
	0·55	0·6	0·4	0·6	0·75	0·35	0·65	0·5	Ten days drought followed by 6 days rain.
	1·2	1·0	0·8	0·9	1·25	1·15	2·3	1·15	Four weeks drought followed by 24 hours rain.
	1·3	0·65	0·2	0·65	1·25	0·7	1·25	0·7	Two weeks drought followed by 12 hours intermittent rain.

TABLE 3.—Average Uranium Content of All Streams Sampled and Rock Types Present in Each Catchment Area.

Tir = Tiroroa facies of Hawks Crag Breccia
DP = Dee Point facies of Hawks Crag Breccia
Gr = granite-gneiss
Ohika = Ohika beds

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Rock type in catchment	100% Gr	100% Gr	100% Gr	100% Tir	100% Tir	100% Tir	50% Tir 50% DP	100% DP	100% Ohika	50% Tir 50% DP	50% Tir 50% DP	100% DP	50% DP 50% Tir	50% DP 50% Tir	50% DP 50% Tir	50% DP 50% Tir	50% DP 50% Tir	20% Ohika 80% Tir
Average uranium content: μg U_3O_8/litre	1·5	1·2	1·3	1·0	1·0	0·8	0·7	0·4	0·4	1·1	0·7	0·5	0·7	1·1	0·7	1·3	0·7	0·9

ficult to predict exactly when a peak value will occur, as this is influenced by both the size of the catchment area of the stream sampled, and by the intensity of the rainfall prior to collecting the sample. An estimate can be made, however, by judging the flow of water in the creek to be sampled. Peak values occur when the flow is between two and four times normal (see Fig. 4).

The causes of the fluctuation in the uranium concentration with changes in weather conditions are not certain, but the following explanation is probable. During drought periods, uranium minerals are leached out of rocks, and are re-deposited as secondary minerals in fissures and on faces by capillary action and evaporation. Some accumulate until a period of heavy rain, when they are flushed out to enrich surface waters draining the catchment area. During a prolonged period of rain, more uranium is present in surface waters than during drought periods. Contributing factors may be grinding action of boulders in flood waters and the increased rate at which slips occur.

VALUE OF THE METHOD IN URANIUM PROSPECTING

There are two possible applications of the method to uranium prospecting: (a) the delineation of favourable areas where the overall uranium content is high, and (b) the discovery of possible economic deposits.

DELINEATION OF FAVOURABLE AREAS

The results shown in Table 4 suggest that the Paparoa granite-gneiss and the Tiroroa facies contain more uranium than either the Dee Point facies or the Ohika beds. As only two local and low-grade uranium occurrences have been found in the Paparoa granite-gneiss, and the background counts are generally high, the high uranium content of the surface water seems to be largely due to sparsely disseminated uranium in the country rock. The low concentration of uranium in creeks draining the Dee Point facies and the Ohika beds is in accordance with the low background counts in these formations, and the lack of evidence

TABLE 4.—Average Uranium Content of Streams Draining Granite-gneiss, Tiroroa Facies, Dee Point Facies, and Ohika Beds Terrain.

	μg U_3O_8/litre
Granite-gneiss	1·3
Tiroroa facies	0·9
Dee Point facies	0·4
Ohika Beds	0·4

to suggest presence of uranium-bearing horizons or lodes. The high uranium content of the waters draining the Tiroroa facies may derive from both the sparsely disseminated uranium in the country rock and from the bedded uraniferous horizons where uranium is concentrated to a marked degree.

This method of geochemical prospecting, together with geological information, can be used to indicate favourable areas for uranium mineralization. In the Lower Buller Gorge, these areas have already been described (Beck *et al.*, 1958), and the method has no practical application.

DISCOVERY OF URANIUM DEPOSITS

The results from samples taken at the mouths of Hawks Crag Creek, Uranium Creek, and the small tributaries of Hawks Crag Creek (shown as 10, 14, and 16 in Figs 2 and 3), are discussed below.

Hawks Crag Creek

Uraniferous horizons outcrop to the south-west of the mouth of Hawks Crag Creek (Fig. 3). As far as it is known, this is the only locality where uranium horizons occur within the catchment area of this creek. The catchment is 7 sq. miles in area and consists of approximately 50% Dee Point facies and 50% Tiroroa facies. Using the average values of uranium concentration in streams draining Dee Point facies and Tiroroa facies from Table 4, the uranium content of the water is expected to be:

$$0{\cdot}5 \times 0{\cdot}4 + 0{\cdot}5 \times 0{\cdot}9 = 0{\cdot}65\ \mu\text{g } U_3O_8/\text{litre}$$

The results from the samples taken at the mouth of Hawks Crag Creek show that the average uranium content of the water is $0{\cdot}7\ \mu$g U_3O_8/litre. The difference between the theoretical and the measured uranium content is within the experimental error. Thus, the results from the samples taken at the mouth of Hawks Crag Creek do not disclose the presence of the uranium horizons, as the quantity of uranium contributed by these horizons is small compared with that contributed by the country rock.

Uranium Creek

In the area drained by Uranium Creek, eight uraniferous horizons are known. The catchment area consists of 20% Ohika beds and 80% Tiroroa facies. Using the data from Table 4 and neglecting the effect of the uranium horizons, the uranium content of the water at the mouth of the creek is expected to be:

$$0{\cdot}2 \times 0{\cdot}4 + 0{\cdot}8 \times 0{\cdot}9 = 0{\cdot}8\mu\text{g } U_3O_8/\text{litre}$$

Results of water analyses from Uranium Creek show that the average uranium content is 0·9 μg U_3O_8/litre. As in the case of Hawks Crag Creek, the anomaly is too small to show conclusive evidence of the presence of uranium-bearing horizons.

The catchment area of Uranium Creek has been thoroughly prospected. The radioactive horizons outcrop over 0·3 of an acre and their approximate grade is 0·1% U_3O_8. The catchment area is 240 acres and the average uranium content of the country rock is assumed to be 5 p.p.m. (Kerr, 1956). Assuming that the uranium minerals present in the area have the same solubility and the rock has a constant mass permeability, the following relationship between the uranium content of the stream may be assumed:

$$pUw = K\ (Ac \times pUc + Ah \times pUh \qquad \ldots\ldots\ (1)$$

where pUw = concentration of uranium in water
Ac = catchment area
pUc = uranium content of country rock
Ah = outcrop area of lodes or horizons
pUh = grade of lodes or horizons
K = constant

By substituting in (1), it is possible to determine, independently of the results in Table 4, what percentage of the uranium present in the water originates from the radioactive horizons. Substituting in equation (1)

$$0{\cdot}9 = K\ (240 \times 0{\cdot}0005 + 0{\cdot}2 \times 0{\cdot}1)$$
$$= K\ (0{\cdot}12 + 0{\cdot}02)$$

Thus the uranium horizons supply one-sixth of the total uranium content of the water, or 0·15 μg U_3O_8/litre.

For a geochemical prospecting programme, probably only one sample would be taken at each locality, and, as the laboratory procedure is accurate only to ± 0·25 μg U_3O_8/litre, the horizons in both Hawks Crag Creek and Uranium Creek could not be detected from samples taken at the mouths of these creeks.

Small Tributaries on the Western Side of Hawks Crag Creek

The catchment areas of the streams represented by the sampling points 10, 14, and 16 consist of approximately 50% Dee Point facies and 50% Tiroroa facies, as does the area drained by Hawks Crag Creek. Thus, neglecting the effect of the uranium horizons, the uranium horizons, the uranium content of the streams at the sampling points is expected to be 0·65 μg U_3O_8/litre. The results from samples taken at points 10, 14, and 16 show positive anomalies of 0·45, 0·45, and 0·65 μg U_3O_8/litre respectively, suggesting that considerable quantities of uranium are leached out of the radioactive horizons in the catchments of these streams. The streams are approximately ¼ mile long and their catchment areas are between 15 and 30 acres.

The examples show that uraniferous horizons, of similar extent and grade found to date in the Lower Buller Gorge, can only be detected by geochemical methods when the catchment area represented by the sample is very small.

Thus, the geochemical method of prospecting has little practical application in the Lower Buller Gorge particularly as a far simpler and more effective method is available.

The uranium horizons are resistant to weathering and are well cemented, with the result that boulders from these horizons are frequently found in stream beds, a mile or more from their source. With a good sintillometer, it is not difficult to trace these boulders to their source.

In some areas, geochemical methods of prospecting may be of considerable importance—e.g., in a locality where, due to depth of weathering, topography or nature of rock, no radioactive boulders are found, and radioactive anomalies on the surface are weak. Here, prospecting by the use of a scintillometer or geiger counter is difficult, and geochemical methods may then assume great importance.

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THE GRADED SEDIMENTS OF THE MAHOENUI FORMATION (KING COUNTRY, NORTH ISLAND)

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(Received for publication, 17 March 1959)

Summary

The graded beds of the Mahoenui formation (Upper Oligocene) are confined to a fairly narrow zone with a north-south trend; narrow in the north (south-east of Te Kuiti) and broadening out to the south on either side of Taumarunui. The beds are graded from fine to medium argillaceous sandstone at the base to silt or clay at the top. The orientation of plant fragments and the under surfaces of sandstones commonly show linear features which have a very marked north-south trend. Flute casts are usually weak to absent. Where present, they show anomalous directions for the source of supply of the sediments. Many flute casts suggest a sediment origin in the south, but others, combined with current bedding on the flanks of the area, and overturning of convolutions within the sandstones, indicate a northern source of supply. Considering all the available data, it is suggested that a northern source area for the sediments is more probable. The graded beds are interpreted as having been deposited, in part, by turbidity currents initiated by the flooding of a major river flowing from the north.

INTRODUCTION

The nature of alternating sandstones and mudstones of the Mahoenui formation was first recognized by J. C. Schofield (1954), who pointed out the similarity between these sediments and the graded beds described by Kuenen and Migliorini (1950).

The observations of Schofield were checked in the field in December 1956, but the opportunity to trace these beds in some detail did not occur until March 1958, when a further 14 days were spent in the field. The results of this recent field work are described below.

DISTRIBUTION

The graded beds of the Mahoenui formation are confined to a narrow strip of the King Country, Taranaki, of a maximum width of 6 miles in the north (south-east of Te Kuiti), widening to 20 miles to the south of Taumarunui, with a possible maximum width in excess of 30 miles.

The most northerly outcrop of graded beds is in the neighbourhood of Mangapehi, and the most southerly in a branch of the Upper Retaruke River, west of National Park. The western zone of transition from graded beds to massive mudstone varies in width from ½ to 2 miles. To the east, the transformation to massive mudstone is much more gradual, with the percentage of sandstone diminishing eastwards over a distance of 3 to 6 miles.

N.Z. J. Geol. Geophys. 2 : 613-21.

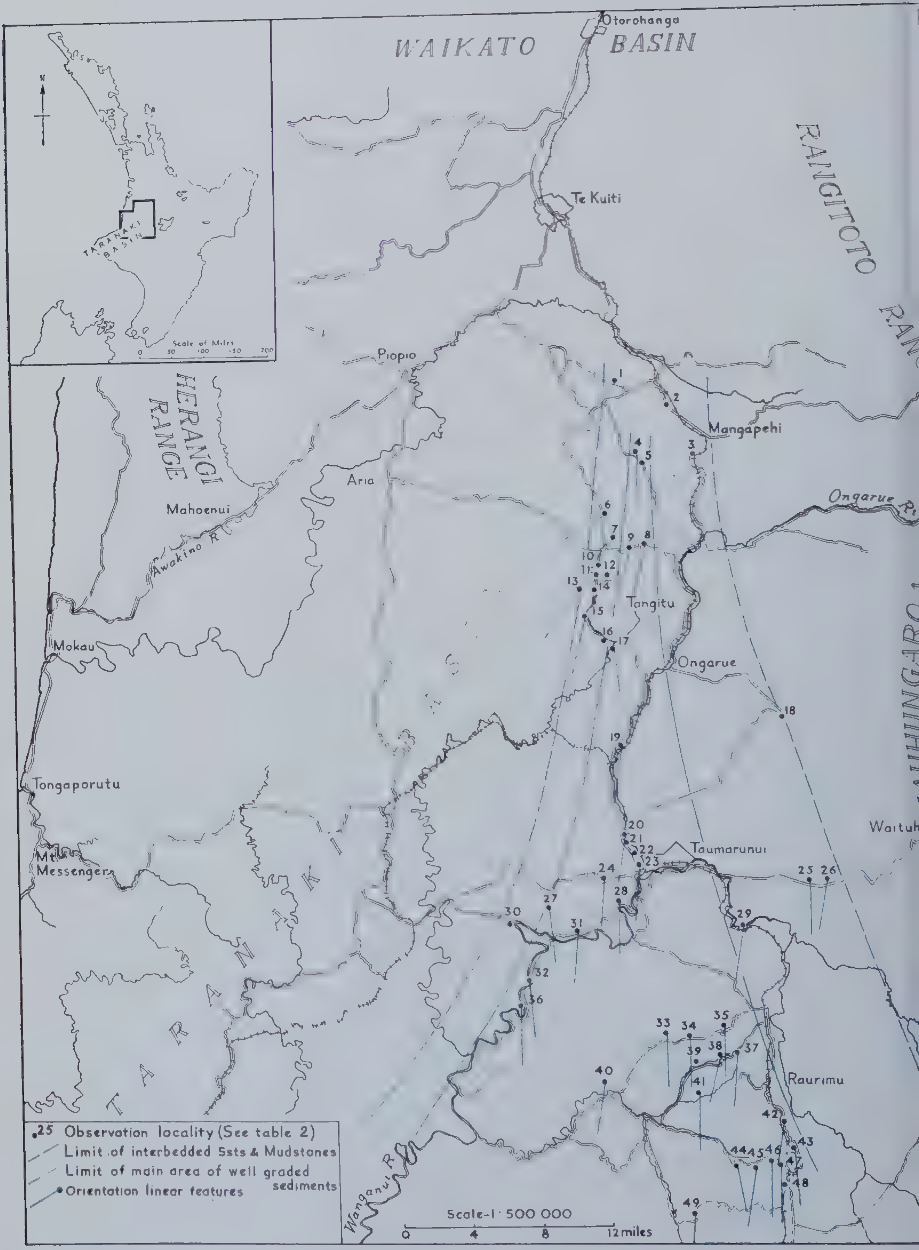

FIG. 1.—Map showing extent of the graded Mahoenui formation. Locality numbers correspond with those given in Table 1.

The distance from north to south over which the graded beds can be seen is about 50 miles. The known area covered by the beds is of the order of 1,000 square miles.

LITHOLOGY

Within the area covered by the graded sediments (Fig. 1, Table 1), the strata consist of a monotonous succession of interbedded sandstones and mudstones averaging about one sandstone band per foot and

TABLE 1.—Summary of Outcrop Data of the Mahoenui Graded Beds.

	LOCALITY	INDICATIONS ON SOLE OF SANDSTONES	ORIENTATION OF LINEAR FEATURES	SANDSTONE BANDS PER METRE	% SANDSTONE PER OUTCROP	PLANT FRAGMENTS	REMARKS
1	Pukerimu Road	b, d.	N 220° E ?	2 — 6	45	—	(CB) CO
2	Kopaki—Mangapehi Road	—	—	6	45	—	
3	1 Mile South of Mangapehi	—	—	4 — 5	50	very fine	(CB)
4	Upper Mapara Stream	(a),(b), d.	N 180-185 E	—	—		
5	Waewaepitau Stream	(b), (d).	N 195 E ?	4	65		(CB) (CO)
[illegible]	1 Mile South of McBeth Road	d. almost flat	N 230-250 E	4	75		(CB) CO
7	½ Mile North of Waimiha Turn-off	d. almost flat	N 230 E ?	2 — 3·5	60		
8	East of saddle, Waimiha Road	(a), b.	N 195 E	4·5	25		
9	West of saddle, Waimiha Road	(a), b.	N 195 E				
10	North side of Tangitu Hill	(b), (d)	N 230 E ?	2·5	50		
11	Top, North side of Hill	g.	—	2 — 3	10		
12	Top, South side of Hill	(b), d, e	N 250 E	1·5 — 3	35		(CO) β
13	Tapuiwahine Hill	(d), g.	N 220 E ?	3	10		
14	South of Tapuiwahine Road	b, c.	N 240 E	1·5	55		
15	North of Otangiwai Road	(a), b, d.	N 195 E				
16	North of Ohura Turn-off	(a), b, c, d, f.	N 175 E	3	15	very fine	
17	South of Ohura Turn-off	(a), g	N 170-180 E				
18	Upper Mangakahu Stream	g.	N 180 E ?	3	10	—	(CB)
19	1 Mile North of Okahukura	(a), b, c, e.	N 185-195 E	2	35		
20	2 Miles North of Taumarunui	(a), d, f.	N 185-195 E	2	10	1·5 cm	
21	1 Mile North of Taumarunui	(a), d.	N 190 E				
22	½ Mile North of Taumarunui	(a), d, (f).	N 190 E	2·5	20	·25 cm	
23	North of Ongarue Road Bridge	(a), b, c, d, e, f.	N 185 E	3	25	4 cm	
24	Kururau Hill	(a), d.	N 185 E	2·5	25	1 cm	
25	5 Miles East of Manunui	(a), (d).	N 180 E ?	5	20		
26	6 Miles East of Manunui	(a), (d).	N 190 E ?	2	15 – 25	1 cm	(CB)
27	Otunui Road	g.	N 175 E	3·5	20	5 cm	CB
28	Herlihy Bluff	(a), b, c, d, e.	N 180 E	2 — 3·75			
29	South of Piriaka	(a), d, f.	N 190 E	5	15	4 cm	(CB)
30	Aukopae	d, g.	—			1 cm	CB
31	Te Maire Bluff	(a), b, c, d, e, f.	N 185 E	5	35	1 cm	
32	Kirikau Road North	(a), b, c, d, e, f.	N 175 E	3·5	55	1 cm	CB
33	Kawautahi Road West	(a), b, d.	N 180 E	3·5	40	·25 cm	CB
34	Kawautahi Road Centre	(a), b, c, d, e, f.	N 180 E	2·5 — 5	50	1 cm	
35	Kawautahi Road East	(a), b, d, e.	N 180 E	3·5	55		
36	Kirikau Road South	(a), b.	N 180 E	3·5			
37	Te Patua East	(a), b, c, d, e.	N 185 E	2·5 — 5	60	15 cm	CO
38	Te Patua West	(a), b, d.	N 195 E	4		1 cm	
39	Oio Stream West	(a), d.	N 180 E	3	40	1 cm	
40	Pukeatua Road	(a), b, d.	N 190 E	3·5	25	·25 cm	
41	Oio Stream East	(a), d.	N 180 E	2	55	·25 cm	(β)
42	4 Miles North of Raurimu	(a), b, d, (e), (f).	N 185-195 E	2·5	30	1 cm	
43	2 Miles North of Raurimu	(a), b, d.	N 175 E	2·5	45		
44	5 Miles West of Raurimu	(a), b, d.	N 170 E	5	40	3 cm	
45	3 Miles West of Raurimu	(a), b, d.	N 190 E	1·5	60	2 cm	
46	2 Miles West of Raurimu	(a), b, d.	N 180 E	3 — 3·5	55	·25 cm	
47	1 Mile West of Raurimu	(a), b, d.	N 180 E	4·5	50	·25 cm	
48	1 Mile South of Raurimu	(a), (d).	N 180 E	3	40	·5 cm	
49	Upper Retaruke River	(a), b, d, e.	N 185 E	4	65	2 cm	β

a	flute casts	e	organism trails	CB	current bedded
b	load casts	f	fossil fragments	CO	convolute bedded
c	drag marks	g	flat or almost flat	β	bored top of mudstone
d	rippled surface				

with a range from $\frac{1}{3}$ to 2 bands per foot. Each graded unit consists essentially of a lower argillaceous sandstone which fines upwards to a siltstone and finally a mudstone. There is usually quite a sharp change in the type of weathering, which affects the lower, sandier portion of a bed less than the upper, more argillaceous part in which weathering obscures the sedimentary features. At a certain point, the clay fraction becomes great enough to produce typical conchoidal weathering when fresh. Although still very silty at this point, the clay-rich beds are referred to as "mudstones" in this paper, and the harder argillaceous sandstones as "sandstones". The percentage of sandstones shown in Table 2 all refer to that portion which looks like a sandstone from a distance, or is readily recognized as a sandstone.

The "sandstones" are argillaceous, calcareous when fresh, and graded from fine to medium grain at the base to a very fine sandstone or siltstone at the top. The "mudstones" have a maximum grain size equivalent to silt at the base, and fine upwards in most cases to clay. It was not possible to discern a layer of pure lutite at the very top.

The contacts between the sandstones and underlying mudstones are usually sharp. They readily separate to expose on the under-surface of the sandstones flute casts, drag marks, and ripple marks (all showing a preferred north-south orientation), and irregular tracks and trails with a random orientation which are presumed to have been left by marine organisms (see also, Kuenen, 1957). Shell fragments and small shells, including two echinoderms, have also been found scattered throughout

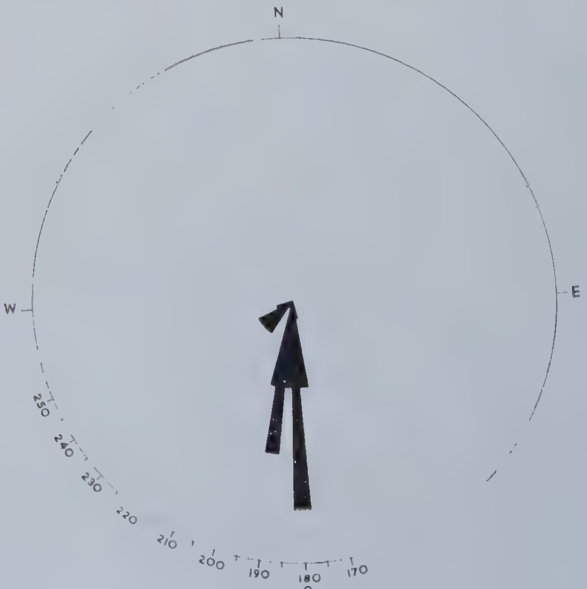

FIG. 2.—Rose diagram of orientations of linear features. Total number is 44. Scale: 2·5 cm for one observation.

most sandstones, and in very small amounts in the mudstones. Although usually finely disintegrated, whole plant leaves and pieces of wood up to 6 inches in length have been seen. The volume of the largest piece of wood seen was about 6 cu.in. The larger plant fragments generally show a preferred north-south orientation of their long axes.

In the ripple-marked portion of the sandstones, slight convolute bedding is usually difficult to see. This type of bedding is more pronounced near the margins of the area, and in the north.

The orientations of weak flute casts, drag marks, ripple and current bedding, and plant fragments have all been mapped in some detail. They show a marked general tendency to align themselves north-south (Fig. 2). Current bedding on the flanks of the area, overturning of convolutions within the sandstones, and current directions as indicated by some flute casts all combine with the paleogeographical picture and the known variations in thickness to suggest a source of supply from the north. Many of the weak flute casts, however, suggest, alternatively, a source of supply from the south. This problem of anomalous current directions is discussed below. One group of weak linear structures in the region of Tangitu shows a southwest-northeast trend. A suggested explanation for this is also discussed below.

North of Tangitu, and along the flanks of the area, linear features are generally very weak. The under surfaces of most of the sandstones are almost flat; flute casts are almost absent. Current bedding is, however, more strongly developed, and in some cases is found right to the base of the sandstones. Flakes of mudstone were found just beneath the convolute bedding at Pukerimu Road (see Table 1).

Borings were noted in a few places from the base of a sandstone down into the underlying mudstone. The greatest depth of penetration into the mudstone was about 16 inches; this boring was seen just south of Tangitu. No signs of borings were noted in the sandstones.

Flanking the area of graded bedding, the sediments consist of massive mudstones to silty marls. Bedding is weak to absent, although dips can occasionaly be measured on concretionary layers.

East of Te Kuiti, and north of the area of graded bedding, the Mahoenui formation is represented by a sandy mudstone overlain by an argillaceous sandstone of Hutchinsonian age. Thin streaks of sandstones have been found interbedded with massive mudstones south-west of Te Kuiti.

AGE

Foraminifera are rather scarce in the graded beds of the Mahoenui formation. Determinations made so far suggest that they range from Waitakian to Otaian and possibly Hutchinsonian. The massive mudstones of the Mahoenui formation have been dated more precisely, and are seen to range from Upper Waitakian to Otaian over most of the basin, with Hutchinsonian faunas in the north. The graded beds are considered to cover a similar age range as the massive beds.

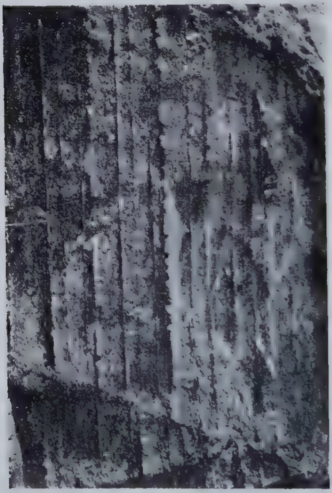

Fig. 3.—Graded beds about ½ mile to the north of Tangitu Hill (locality 11).
—*Photo, J. van der Sijp*

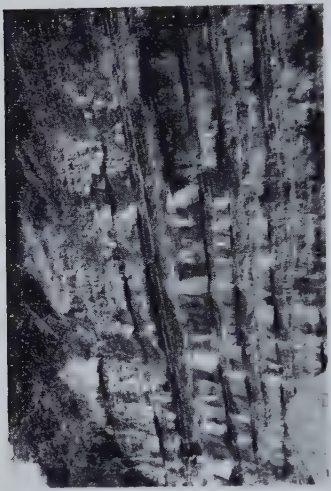

Fig. 4.—Graded beds south of the Ohura "turn-off" (locality 17).
—*Photo, J. van der Sijp*

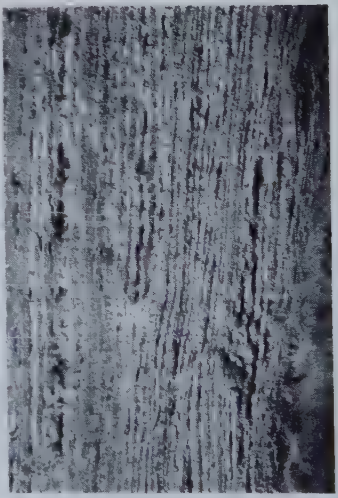

Fig. 5.—Graded beds along the Kirikau Road (locality 32). (Length of stick, 2m.)
—*Photo, J. van der Sijp*

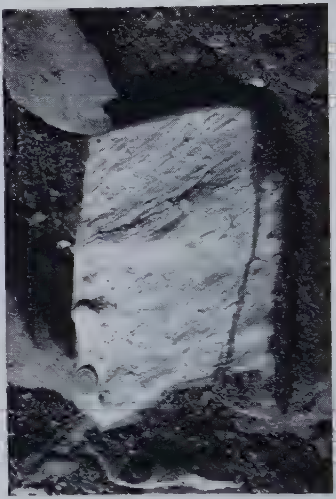

Fig. 6.—Detail of the undersurface of a sandstone bed; Kawautahi Road (locality 34). (Diameter of coin, 28 mm.)
—*Photo, J. van der Sijp*

Considerable difficulty was experienced in the field in trying to separate the sandstones of Hutchinsonian age (Mahoenui formation) from sandstones of Altonian age (Mokau formation). It is suspected that these sandstones are diachronous (Table 2). Lithologically, they should be referred to as the Mokau formation.

Origin of the Graded Beds

The source of sediment supply as suggested by the known paleogeography of the Taranaki Basin, thickness differences of the Mahoenui formation, the areal distribution of the graded beds, and current direc-

TABLE 2.

	S.	TARANAKI BASIN	N.
	STAGE	FORMATION	STAGE
	Altonian	Mokau	Altonian
			Hutchinsonian
OLIGOCENE	Hutchinsonian	Mahoenui	
			Otaian
	Otaian		
			Waitakian
	Waitakian	Te Kuiti	
			Duntroonian
	Duntroonian	Mangaotaki	
			Whaingaroan
	Whaingaroan		
			Eocene?
	Eocene?		
	Mesozoic Greywacke Series		

tional features as indicated by current bedding, overturning of the crests of convolute bedding, and by some flute casts, all suggest that the sediments have been derived from the north by a high-density turbidity current probably of the type described by Kuenen and Migliorini (1950). However, the indication of current directions from the south, as suggested by many of the flute casts, cannot be ignored. Anomalous current directions from evidence of flute casts have been found recently in many different areas of graded sediments. In the Cambrian of the Harlech Dome, Jones (1955) points out that the source directions suggested by Kopstein (1954) are the opposite of those that would be deduced from the paleogeography of the area. Recently, Mr E. K. Walton (pers. comm.) has found current directions which are the reverse of those given by Kopstein.

Work in progress by B.P.M. (Holland) suggests that anomalous directions have also been found from sole markings in the Kulm and

Floetzleeres greywackes of Sauerland and Oberhartz in Germany, originally described by Kuenen and Saunders (1956, as well as in English carboniferous greywackes. Such anomalies suggest two possibilities:

(1) That the sediments were derived from two different, and in some cases, opposing source areas, possibly on opposite sides of a basin, or from different points on the same side of the basin.

(2) That interpretation of current direction from evidence exclusively of sole markings is unreliable. The trend of the current movement would probably be correct.

Whichever suggestion is correct—and where weak sole markings are concerned the solution may well incorporate both—it is becoming increasingly apparent that deduction of source area exclusively on the evidence of sole markings must be treated with reserve.

From assessment of all the available information, a major source of supply from the north is postulated for the area under consideration. The northern extremity of the main area of graded bed deposition is just north of Tangitu. On either flank, currents of lower density (and therefore slower moving) deposited the current bedded sandstones which show few or no linear features. Similar characteristics north of Tangitu indicate that here only the low-density aftermath of the main flow deposited detritus. Still further north, but south of Te Kuiti, was an area of transportation and no accumulation of sediments on which the turbidity currents could have been initiated. Another smaller source area to the northeast of Tangitu is suggested by the northeast-southwest trending lineations of this area. A possible continuation of these beds to the northeast could have been removed by post-Mahoenui fault uplift and erosion.

CONCLUSIONS

(1) The graded beds of the Mahoenui formation are confined to a narrow belt; narrower in the north, widening to the south.

(2) They were deposited by high-density turbidity currents in what was probably a tectonically controlled north-south channel.

(3) The bulk of the sediments was probably derived from a south-flowing river characterized by periodic flooding. The turbidity currents were initiated south of the stable "Piopio Threshold".

(4) Conflicting evidence from flute casts suggest the possibility of sediments also being derived from the south. Interpretation of current directions from these features must be treated with reserve, especially when they are poorly developed. A detailed study of the sand grain sizes might help to solve the problem of provenance.

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HEAVY MINERALS FROM SOUTHLAND

PART I: PERMIAN–JURASSIC SEDIMENTS

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Summary

The greater proportion of heavy grains in the Permian to Jurassic sedimentary rocks are either stable detrital minerals which have survived intrastratal solution, or authigenic minerals produced by diagenetic alteration. Mineralogical elements of detrital origin in the rocks represent a wide variety of provenance areas. There are strong flushes of certain mineral groups of igneous origin, but these minerals have been partly altered by percolating solutions. The combined effects of sedimentary processes during deposition, and post-depositional diagenesis, have produced in these Permian-Jurassic rocks a relatively stable heavy mineral assemblage containing zircon, tourmaline, apatite, and authigenic granular epidote.

INTRODUCTION

During a traverse across Southland, eastwards from Tuatapere and Orepuki, the writer collected grab samples from outcrops of Upper Paleozoic and Mesozoic sediments for heavy mineral studies. A number of hand specimens were taken from the greywacke fault block immediately to the east of Ohai, where there are various lithologies from (?)Lower Triassic to Upper Triassic in age.

Full statements on the lithology and the detrital rock-fragment content for beds of similar age in Southland have been given by Coombs (1950) and by Wood (1956). These writers have shown that the distributive province in this area during the Upper Paleozoic and Mesozoic received a variety of detritus, as seen in rock chips and pebbles, representing basic to acid plutonic and volcanic material, indurated sediments, and various regional and contact schists. Outburst of volcanic activity provided additional flushes of tuffaceous ejecta.

The present study aims to describe the general character of the heavy mineral suites in greater detail so that these may be used as differentials in investigating the provenance of Cretaceous and Tertiary covering sediments. In this respect, the older rocks as a whole have been found to be characterized by a more limited suite of stable heavy minerals than would be expected in view of the exotic nature of their pebble constituents. Evidence of intrastratal solution and diagenetic alteration of many detrital fragments, such as pyroxene and mica, is clearly seen in grain mounts, so that, although these minerals are present in important quantities in some Mesozoic sediments, it is doubtful if they could have survived weathering and re-deposition during Tertiary sedimentation. Removal of the less stable, heavy minerals by diagenetic processes is reflected in the data of Table 1, which show a predomination of apatite

N.Z. J. Geol. Geophys. 2 : 622-33.

TABLE 1.—Heavy Mineral List, Giving Grains % of the Non-opaque Fraction

	S178/ 1000	S178/ 1004	S170/ 1000	S169/ 1001	S169/ 1007	S159/ 1000	S159/ 1003	S159 1012	S159 1013	S159/ 1017	S159/ 1021	S159/ 1011	S159/ 1023	S170/ 1008	S160/ 1000	S160/ 1003
Anatase		*r*												*r*		
Apatite "A"		49·8	58·8	15·2	62·5	9·1	43·0	14·3	8·7	21·0	26·7	4·6	50·3	37·4		14·6
Apatite "B"		2·4	4·4	*r*	3·9	2·1	*r*	*r*	*r*	*r*	2·7		5·3	6·3		2·1
Augite			*r*	*r*		88·6	*r*	*r*	*r*		*r*			*r*	*r*	*r*
Biotite		*r*	11·4	*r*	*r*		*r*	10·1	*r*	*r*	*r*	3·8	*r*			*r*
Chlorite	*r*	*r*	*r*	23·5	6·6	*r*	*r*	*r*	*r*	*r*	29·1	*r*	13·4		8·6	5·3
Epidote	6·3	8·1	9·1	45·3	9·9		*r*	54·9	46·6	46·5	15·3	*r*	11·6	8·4	68·3	53·6
Garnet	*r*	*r*	*r*	*r*	*r*	*r*	*r*	*r*	7·6	*r*	*r*		*r*		1·3	*r*
Hornblende	86·1	*r*	*r*	*r*	*r*	*r*	*r*		*r*			90·0	*r*	36·1		
Kyanite							*r*								*r*	
Opaques	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Pyrite			×				×									
Rutile		*r*				*r*		*r*	*r*	*r*			*r*			*r*
Sphene	*r*				*r*		*r*	*r*	8·7		*r*	*r*	*r*			*r*
Tourmaline	*r*	*r*	*r*	*r*	*r*		*r*		*r*					*r*	*r*	*r*
Zircon	5·7	18·4	15·4	16·6	17·7	*r*	56·9	20·2	27·8	33·2	27·0	1·4	18·1	10·5	21·7	21·4
Zoisite		*r*	*r*	*r*			*r*	*r*	*r*	*r*	*r*		*r*	*r*	*r*	*r*

and zircon, both of detrital origin, together with authigenic epidote and chlorite. Even when outstanding quantities of amphibole and pyroxene are present in sandstones, these grains generally show an advanced degree of destruction in that they have been sharply etched and pitted by intrastratal solutions.

Wherever possible, fine to medium grained rocks were selected for the heavy mineral extractions, but no examination was made of the matrices of conglomerates. Table 2 provides localities and field descriptions of the rocks which have been examined to furnish the data of Table 1.

TABLE 2.—Field Data of Samples

Sample No.	Grid Reference	Age	Description
S159/1000	086638P	Upper Triassic	Grey blocky sandstone of even but coarse grade; non-calcareous
S159/1003	072658P	Upper Triassic	Fine-grained dark grey sandstone, strongly indurated
S159/1011	008604P	(?)Lower Triassic	Dark grey sandstone
S159/1012	064667P	Upper Triassic	Medium grade, grey sandstone
S159/1013	031660P	Middle Triassic	Light grey sandstone
S159/1017	037668P	Middle Triassic	Coarse sandstone
S159/1021	034637P	Middle Triassic	Dark grey sandstone
S159/1023	014630P	(?)Lower Triassic	Grey-green sandstone
S160/1000	745682P	Permian	Non-calcareous, pink sandstone
S160/1003	707738P	Permian	Finely jointed pink sandstone
S169/1001	685496P	Kaihikuian	Strong, fine-grained dark sandstone
S169/1007	702508P	below Kaihiku sandstone	Calcareous dark grey-green sandstone
S170/1000	862423P	Otapirian	Dark green indurated sandstone
S170/1008	026393P	Permian	Structureless bioclastic with *Maitaia* fragments
S178/1000	778297P	Upper Jurassic	Dark grey fossiliferous sandstone
S178/1044	086040P	Jurassic	Light grey sandstone

EXPERIMENTAL TECHNIQUES

Several laboratory methods were devised to disaggregate the detrital grains of these rocks to facilitate the assembly of quantitative data of minerals present in the heavy fractions. From the outset, grinding of the samples with a steel pestle and mortar was avoided and chemical solution of the matrix was abandoned, as most minerals were attacked to some extent by acids. The methods which proved to be most useful were those that made use of expansive forces arising from crystallization in the pore spaces of the rocks. The following were found to be satisfactory:

Freezing in Distilled Water

This method was quite effective with the less indurated Jurassic sandstones. The dried sample was placed in an evacuating flask and the air drawn off by means of a water pump developing a vacuum pressure of 20 mm. When the flask was exhausted, cold distilled water, with a small amount of Teepol added, was introduced from above. After sufficient time had elapsed for the pore spaces to be inundated (usually half an hour), the sample was transferred to a beaker seated in a vessel containing solid carbon dioxide, where the process of freezing was continued for about an hour. The rock chips were removed and heated in fresh water to melt the ice and allow disrupted fragments to fall away. If disaggregation was not complete, the process of freeze and thaw was repeated several times. Many fragments disrupted in this way were not monomineralic, but usually the grain aggregations were sufficiently weakened to be broken down with a rubber pestle.

Impregnation with Saturated Solutions of Sodium Sulphate

For indurated Triassic rocks, considerable success was achieved with a "freeze and thaw" method, using a saturated solution of sodium sulphate. The rock sample was inundated with the solution at boiling point in a fashion similar to that described above. After the salt had crystallized, it was re-dissolved in warm water to bring about disaggregation.

In many instances, the rock did not yield, and the process was taken a stage further by high-temperature and high-pressure concentration of the sodium sulphate solution. This technique has been successfully applied by Taylor and Georgeson (1933), working at temperatures and pressures well above those used by Driver (1928) to force the salt into the pore spaces. The advantage of the method lies in the higher solubility of sodium sulphate at elevated temperature and pressure, and in the subsequent rapid crystallization, effecting a greater disruption of the sample. The present work has shown that an increase in pressure does not materially affect the process of pore space inundation; this seems to be achieved as completely as possible by the vacuum method described above.

A mild steel tube, 18 in. long and 5 in. in diameter, with a bore of 2 in., was adapted as a high-pressure container. A heavy flange was screwed on at each end and two steel caps were bolted to the flanges, the junctions being sealed by boiler gaskets. In one cap, two outlets led to a pressure gauge and to a needle-controlled emergency valve. All threaded joints were sealed with graphite grease and asbestos wool and the whole container was wrapped with asbestos paper to diffuse the heat applied externally. The apparatus was mounted vertically on a platform covered with sheet asbestos. The rock sample, together with the solution and an excess of the salt, was contained in a Maxon boiling tube which rested at the base of the steel container in a solution of sodium sulphate. The time taken for heating varied from 3 hr to 5 hr and pressures ranged from 280 lb to 400 lb per sq. in., depending on the nature of the rock being treated. The container was cooled rapidly and the rock fragments were removed and allowed to dry.

After disaggregation, the samples were screened and heavy minerals were concentrated by sedimentation through tetrabromethane (acetylene tetrabromide) in a separating funnel, or by centrifuging where grain size was small. When each concentrate had been quartered with a micro-sample splitter, one portion was permanently mounted in Canada balsam and the other was examined in cedar oil (r.i. = 1·51) or clove oil (r.i. = 1·54).

MINERALOGY OF THE HEAVY CONCENTRATES

In Table 1, the presence of opaque minerals is indicated by ×. The opaques generally constitute 70% to 85% of the heavy fraction, but quantities for them are not quoted in the table, which is designed specifically to show the differentiation of the more diagnostic non-opaque fraction. Percentages of these minerals are therefore quoted with reference to the total non-opaque fraction; *r* is used to indicate $<1\%$ for any mineral. In no case did the total heavy minerals exceed more than 3% by weight of sample. Percentages have been calculated from counts of 300 to 400 grains in each slide.

Anatase

Minute crystals of authigenic anatase were located in association with granular masses of ilmenite in two samples. The crystals are partially coated with opaque material, but an euhedron $\{111\}$ was identified in a Permian bioclastic rock (S170/1008).

Apatite

Apatite is absent from only two of the rocks that were sampled; in all others, this mineral is a major constituent of the heavy concentrate, and it is persistent both in appearance and in habit. Two varieties have been distinguished, one colourless and nonpleochroic (Apatite "A") and the other pleochroic (Apatite "B"). The commonest habit for both varieties is prismatic with $\{10\bar{1}0\}$ terminated either by a rough parting parallel to the base or by a "euthedal-worn" form $\{10\bar{1}1\}$, the faces of which are discernible although interfacial and solid angles have been rounded by abrasion. As often as not, the pyramidal faces are truncated by $\{0001\}$ and a few crystals show hemimorphic development of (0001). This prismatic form ranges in size from 0·20 mm by 0·03 mm to 0·07 mm by 0·02 mm; length-to-breadth ratios lie between 7:1 and 1:1.

Non-pleochroic apatite is typically clear and colourless, with a faint greenish lustre. Inclusions are not common, but vary in type from specks and rods of opaque dust aligned parallel to the base or to *c* crystallographic axis, to elongated euhedral or anhedral apatite crystals with their length parallel to that of the host crystal.

Pleochroic apatite is widely distributed throughout the sediments, but never forms more than 6·3% of the non-opaque heavy minerals. The degree of abrasion, morphological habit, and optical characteristics apart from pleochroism, are the same as those of non-pleochroic apatite, but the effects of intrastratal solution were seen only in the pleochroic variety, where small re-entrants and deep pits occur at the junctions of the basal partings and the prism. Pleochroism seems to be intimately connected with the presence of inclusions, since colour changes are seen only in close proximity to included opaque materials. Maximum absorption is always parallel to length, with the following pleochroic schemes: colourless to light brown or light purple; greyish-green to deep greyish-green; and light brown to deep brown. The inclusions most commonly associated with pleochroism are also those most common in non-pleochroic apatite—i.e., specks and rods of opaque dust, but there are two types of inclusions found only in the pleochroic variety: (a) wide vertical bands or cores which are either black and opaque or brown and pleochroic, with no visible structure and at times no definite margin; (b) brown pleochroic bands similar to those just described, but containing thin opaque rods transverse to their length; the rods do not enter the peripheral colourless apatite. To all appearances, the other types of inclusions are not pleochroic, but they are surrounded by coronas of pleochroism in the otherwise colourless enveloping material. The sphere of influence in the case of rods and specks is very limited, so that the intensity of the pleochroism is greatest where these inclusions are close-packed. For example, one crystal of apatite was pleochroic where the inclusions were confined to each end, but in the centre was colourless. However, the anomaly exists in that exactly the same types of inclusions are present in close formation within colourless apatite and it would seem, therefore, that pleochroism is probably due to a dispersion phenomenon, as suggested by Goldschmidt (in Smithson, 1931).

Apparent secondary growth of apatite was seen in three grains, and in each case a rounded stumpy crystal of the pleochroic variety formed the core. Colourless apatite in optical continuity with the core, but showing no crystal form, made up the rims of secondary material.

Pyroxenes

Pyroxenes appeared in quantity in only one sample, but trace amounts were present in a number of rocks. No crystal form was observed, and the grains are mainly elongate with the extensive pittings and dentate ends which are consistent with intrastratal solution. Apart from these solution features, the fragments are glassy and fresh in appearance. It is significant that no rounded grains were observed, for the pyroxenes are generally believed to be unstable in a cycle of weathering and redeposition, and the absence of rounded fragments points to derivation from a primary volcanic source, as described by Coombs (1950). Two varieties of pyroxene were noted: pleochroic common augite and a paler diopsidic type which occurs more regularly in the heavy suites.

Epidote

Epidote is almost as widely distributed as zircon, and is missing in only one sample. In five samples, members of the epidote group dominate the non-opaque heavy concentrates and grain size is usually less than 0·20 mm, with a maximum of 0·40 mm. The epidotes occur in two distinctive habits. The first type consists of green, clear, "bottle chip" grains of the iron-rich variety which are inclusion-free and show pleochroism in green and yellow. A few euhedral grains are elongated parallel to *b* with strong (001) cleavage.

The second habit is an irregularly shaped composite grain made up of small angular crystals. Epidote in such aggregations is widespread, and it appears even in those samples where the mineral is minor in quantity. Many of the composite grains are turbid and masked by opaque coatings, but others are clear and possess a weak pleochroism from pale green to colourless. Changes in optical properties within the composite grains indicate considerable ranges of composition from iron-rich members to clinozoisitic epidote. The change towards the calcium variety is accompanied by bleaching of colour, increase in 2V, and variation in dispersion to dominant $r<v$. Highly calcic clinozoisite with positive optical sign is rarely present, but in all samples the clinozoisitic varieties are more common than iron-rich types. The granular or composite form of epidote, in large part, is authigenic in origin. In thin sections, it is found in three different settings: along the cleavages in biotite, chloritic biotite, and chlorite pseudomorphs after biotite; associated with chlorite in the matrices; and within saussuritized plagioclase feldspars.

Garnet

Although a rare constituent in the heavy concentrates, pink almandine garnet is notable for its persistent occurrence in all but two samples. The common form of euhedral crystals is {110} with or without {211}, which, when present, may be extraordinarily well developed. Rolled grains are not common, but solution effects have affected the outlines of the dodecahedra, forming a series of steps similar to those described by Smithson (1941). The first sign of solution is a set of teeth-like rhomb patterns which gradually become enlarged yielding pits, and later forming channels. When fully developed, the channels maintain a strong directional trend in each grain. Sharp edged spinose grains, which appear to be the final form before complete solution and which certainly could never have withstood transportation as detritals, point to the authigenic origin of the solution features. Inclusions are rare, but in some garnets small opaque granules are arranged in lines which intersect at angles of 60° and 120°, thus making a pattern of equilateral triangles.

Hornblende

Where it is present in large quantities (S178/1000, S159 1011, S170/1008), presumably derived from a primary volcanic source, hornblende has the form of elongated fresh grains terminated by rough cross fractures and showing solution effects. Pleochroic schemes are varied and the following minimum to maximum absorption colours were observed: light green to brown-green; deep green to blue-green; dusky brown to dark brown; light brown to deep brown-green; light green to medium green. In other samples, where hornblende occurs in rare quantities, the mineral is more altered in appearance and the grains carry deep pits and solution channels. These features, together with the rounded form and a dominant pleochroism in light to medium green, suggest that the grains have passed through an extended process of transport and sedimentation from a parent landmass source quite different from that of the hornblendes first described above.

Opaque Minerals

Ilmenite with leucoxene, or leucoxene alone, are the dominant minerals in the opaque group. Hematite is rare, and magnetite in small octahedra is confined to the tuffaceous rocks. Pyrite occurs in two samples, S170/1000 and S159 1003, as irregular aggregates and as a replacement mineral of foraminiferal-like bodies which are similar in appearance to *Lagena*. Limonite invariably forms a coating on most detrital grains.

Tourmaline

Tourmaline is a consistent member of the heavy mineral suites, although only in small quantities. Prismatic crystals terminated by cross fractures parallel to (0001) or by flattened $\{10\bar{1}1\}$ faces are the commonest type. These grains typically are fresh and angular, with no marks of abrasion on interfacial edges or fractured surfaces. Parallel or radiating groups of authigenic crystals occasionally form bundles containing 12 or more elongated fibrous crystals with length-to-breadth ratios about 10:1, and seated on a host grain. In general, the size range of tourmaline is from 0·34 mm by 0·08 mm to 0·04 mm by 0·01 mm. Pleochroism is strong in all crystals, and a number of varieties of tourmaline could be distinguished in the following dichroic schemes: colourless to deep green, bluish green or greenish brown; pink to deep green or bluish green; yellow to brown; and light yellow to deep green. According to Krynine's (1946) classification of sedimentary tourmalines, the parent sources are mainly plutonic and pegmatite-injected metamorphic terrains.

Zircon

Zircon is the commonest heavy mineral in all samples, usually as euhedra with $\{110\} \pm \{100\}$ terminated by $\{111\} + \{hkl\} \pm \{001\}$. Various types of inclusions, from small zircon rods to fluid or gas cavities and lobate brown bodies, are aligned with respect to zonary lines in the host crystals. Many of the zonary layers show the variation in refractive index discussed by Hutton (1950).

Small pointed secondary outgrowths occur occasionally on the prism faces of both worn and euhedral zircons. Similar growths have been described by many writers as authigenic in origin, particularly where the addition has been made as sharp pyramidal forms on anhedral host crystals. In the Southland examples, there is always a clear line of junction between the "saw-tooth" outgrowths and the host grain, and the development of these secondary materials has invariably been controlled by pyramidal faces. There is optical continuity between the grains and their outgrowths. Brammall (*in* Smithson, 1941, p. 104) has suggested that these authigenic additions may be composed of rare earth materials, but Hutton (1950) has shown that in some New Zealand occurrences the material is zircon, and Poldervaart (1955) has referred to a zirconium cycle promoted by alkaline solutions. Butterfield (1936), Smithson (1937), and Bond (1948) have noted that zircons bearing secondary outgrowths are usually found in shallow water sediments, and it is probable that the Southland rocks fall into the same category.

Zoisite

Zoisite has been identified with certainty in rare amounts as stumpy colourless crystals containing the "microlites" described by Milner (1940). Longitudinal striations are a frequent feature of grain surfaces, and the optic axial plane is located in either of two positions parallel or normal to these striations.

DISCUSSION

One Permian rock (S170/1008) is outstanding as a bioclastic limestone composed of tightly packed elongated rods of calcite with no interstitial material other than thin seams of authigenic calcite. Grains of quartz are rare and a poor heavy-mineral suite is present. The calcite rods have been derived from the polygonal shell prisms of the mollusc *Maitaia* and the commonly circular cross-section of the rods is a result of abrasion or solution. Similar clastic remains of the fossil have been noted by Bell, Clarke, and Marshall (1911), Harris (*in* Wood, 1956) and Reed (1950). The almost complete absence of light minerals other than calcite and the presence of heavy minerals which form about 0·1% by weight of the sample suggest an unusual process of deposition for the sediment. A possible explanation may be that, as sand was winnowed by currents or waves through the shallow off-shore habitat of *Maitaia*, only the heavier minerals were able to settle and thus formed natural concentrates. Some of this material was lodged within the shells, which, upon the death of the molluscs or during storm periods, were swept up on to beaches to form high banks. The typically unstratified appearance of the beds with occasional unbroken shells in all positions of rest indicates such a mode of formation.

Within the heavy concentrates of the sandstones, the commoner allogenic minerals, apatite, zircon, hornblende, tourmaline, and biotite, form a notably restricted suite which appears more or less consistently in all formations. This is the most striking feature of the mineralogy. Other such minerals as rutile are of local occurrence, and augite, generally accepted as an unstable detrital during erosion and transportation, is confined in quantity to one tuffaceous horizon. There is no simplification as the heavy mineralogy of the sediments is traced from older to younger beds. Apatite, zircon, and other resistant detritals persist throughout, but there is a general tendency for larger grains of apatite and zircon in younger Mesozoic rocks to become more rounded.

At first sight, it appears as if the original nature of the heavy mineral suite has largely been concealed or destroyed by diagenetic alteration or, in some cases, by re-working of formations. Diagenetic processes in small part have affected even the stable detrital minerals, since apatite, zircon, and tourmaline exhibit secondary growth. Other detritals display compatible features; for example, garnet is deeply pitted and etched, and hornblende is rare except in remnants of local volcanic flushes. However, there is a strong possibility that the heavy mineral suite originally available as individual grains from weathered parent rocks in the area of provenance was restricted in variety. The best evidence for such a suggestion is the manner in which garnet persists in rare amounts from the Permian through to the Jurassic rocks. Many recorded instances of garnet as an unstable allogene (Sindowski, 1949; Dryden and Dryden, 1946; Hutton, 1950) indicate that this mineral should be among the first to disappear from a parent heavy mineral suite during weathering and re-deposition. Nevertheless, there is sufficient variety among the minerals of various heavy assemblages, even though rare in some cases, to indicate the diversity of parentage already proved from conglomerates by Coombs (1950) and Wood (1956). Tourmaline species point to plutonic and injected parent rocks, while other diagnostic associations are apatite-epidote-sphene-garnet or garnet-hornblende-kyanite-epidote-zoisite (high rank metamorphic), apatite-biotite-hornblende-zircon (acid igneous), augite-rutile (basic igneous), and rounded tourmaline-rounded zircon-rounded granular epidote-leucoxene (re-worked sediments).

The widespread occurrence of authigenic minerals in the Southland rocks is an important feature. Smithson (1941) has shown that the degree of "richness of a suite" of heavy minerals is directly related to authigenic features of the deposit, and where zircon, apatite, etc., show outgrowths the suite has been considerably impoverished by intrastratal solution. Smithson's findings have a general application in the Southland greywackes, for, although the greatest potential source here for authigenic materials seems to have been the chemically active clay matrix, there has nevertheless been solution and reduction even of such minerals as garnet, which has a high resistance to chemical action in subterranean conditions (Smithson, 1941; Pettijohn, 1941).

Minerals of the epidote group are generally classified as unstable under most conditions of weathering (Pettijohn, 1948; Smithson, 1941), but in some Southland rocks it seems probable that authigenic epidote and clinozoisitic epidote have been re-deposited during reworking of the sediments. This is suggested by the roundness of many composite grains and their perfect clarity due to removal by allogenic processes of the usual chloritic or micaceous envelope. The stability of epidote as a detrital mineral is supported by another New Zealand occurrence of similar derived composite grains which have been described by Hutton (1950) from sands on the west coast of Otago.

CONCLUSIONS

The heavy mineralogy indicates four main conclusions:

(a) The Permian-Jurassic sediments contain detrital suites derived from areas of provenance involving parent materials of igneous, metamorphic, and sedimentary nature.

(b) Weathering, erosion, and transport from these areas of provenance greatly reduced the quantity of many of the diagnostic, but unstable, detrital minerals (e.g., pyroxenes, amphiboles), so that a preponderence of the stable types (zircon, apatite, tourmaline) appears regularly in the heavy separates.

(c) Diagenetic processes of reconstitution again altered the heavy-mineral assemblages, certain detrital minerals (e.g., biotite, garnet) being further reduced in quantity, while some authigenic materials (granular epidote, chlorite) increased in amount.

(d) Re-working of the sediments during deposition is indicated by the occurrence of well-rounded grains of zircon, tourmaline, apatite, and authigenic granular epidote; this relatively stable assemblage seems to be representative of the Permian-Jurassic rocks where these have supplied detritus during Cretaceous or Tertiary sedimentation (to be discussed in Part 2).

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DISTURBANCE IN THE IONOSPHERIC F-REGION FOLLOWING THE JOHNSTON ISLAND NUCLEAR EXPLOSION

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Summary

Extensive F-region ionospheric disturbances were recorded at the New Zealand ionospheric stations at Rarotonga, Christchurch, and Campbell Island following the Johnston Island nuclear explosions. From these records, as well as from magnetic recordings made at adjacent stations, the characteristics of the ionospheric movements, and of the gaseous wave which generated them have been deduced. The gaseous wave appears to be a surface wave with velocity greater than that of sound and it has some of the characteristics of a normal shock wave.

INTRODUCTION

The hydrogen bombs exploded at high altitudes near Johnston Island (Fig. 1) on 1 and 12 August 1958 produced large effects on the ionospheric F-region at Rarotonga. Details of heights of explosion and energy of the bombs have not been officially released, but from various manifestations it is considered that the heights were approximately 160 km and 100 km and the energies were about 10^{24} ergs. A considerable fraction of this energy appeared as radiation capable of ionizing the atmosphere at the D layer level; this effect extended outwards to at least 15° from Johnston Island. In the F-region, however, the amount of ionization was insignificant. Factors which could have affected the F-region were, hydromagnetic pulses, electrostatic waves, and blast waves. The effects at Rarotonga can be explained in terms of this last factor, and, for reasons given later, it seems that the first two factors are insignificant.

OBSERVED DATA

Figure 2 shows the distribution of ionization with time deduced, with considerable interpolation, from ten minute recordings taken during the first event. The interpolation was performed by considering the detailed analysis of the second event, during which two-minute recordings and excellent ionograms were obtained (see Fig. 3). Figure 4 gives the virtual height records of the first event. As will be seen, after $01^h:20^m$ the ionization above 560 km appears unaffected by the passage of the disturbance, while below this height there is no trace of the normally observed ionization. It will be seen that the effects of the second event were much smaller at Rarotonga, and were not observable at other

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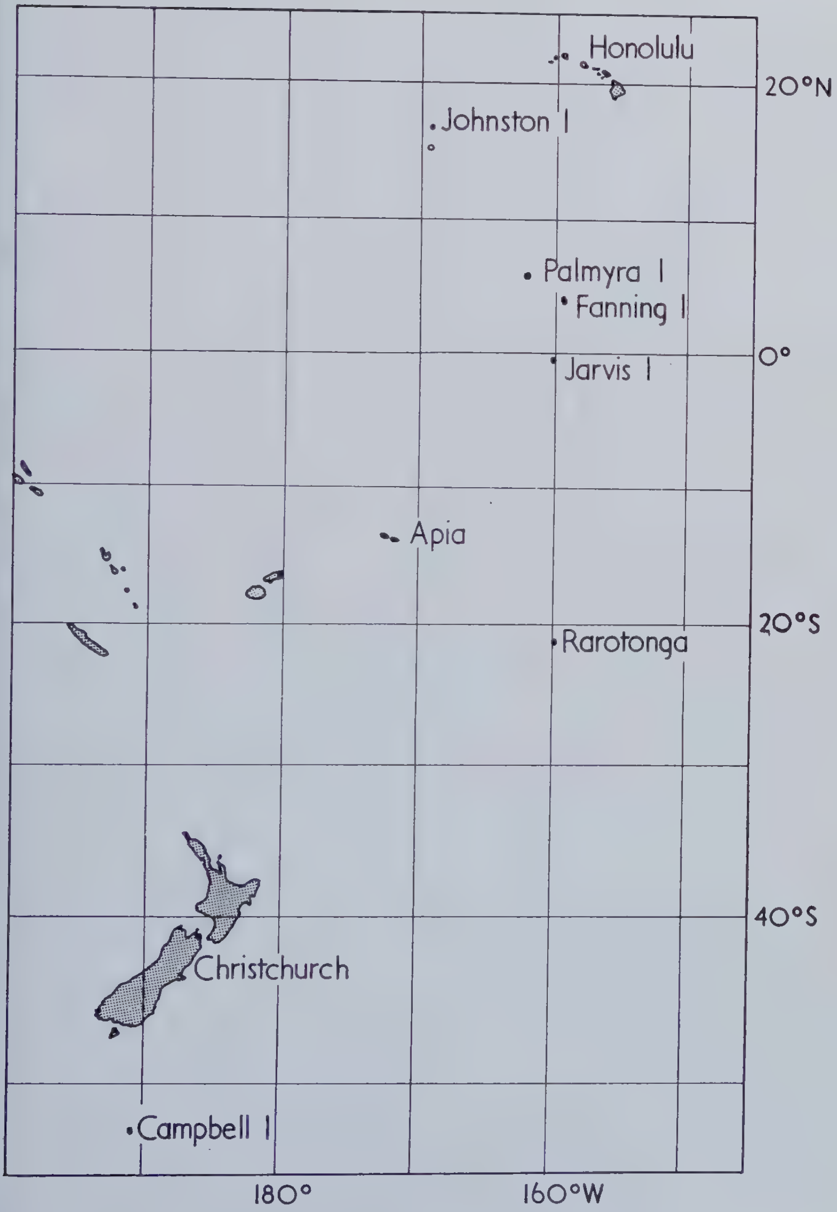

FIG. 1.—Locality Map.

The open circle 1½° south of Johnston Island represents the assumed explosion point.

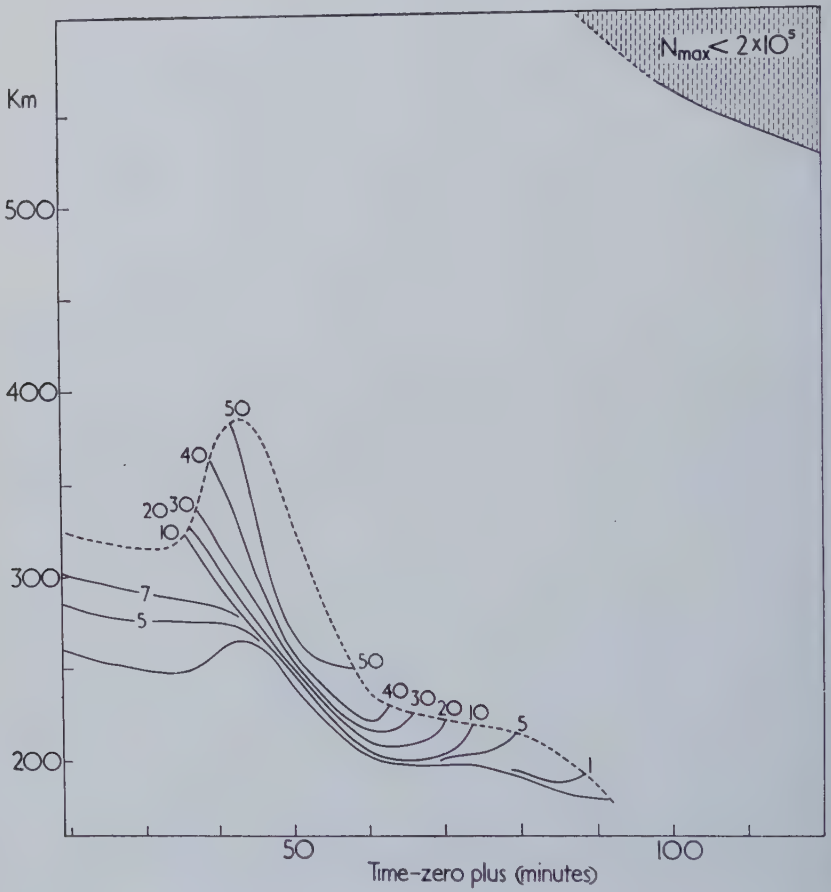

FIG. 2.—Contours of equal electron density over Rarotonga deduced by true height analysis for the first event. Contours are in units of 10^5 electrons per c.c.; time is measured in minutes from the time of explosion.

New Zealand stations, so that the discussion which follows refers only to the first event.

Figure 5 is the f-plots for Christchurch and Campbell Island on 1 August. Through the courtesy of Messrs J. A. Lawrie and V. B. Gerard, the magnetic vectors which these workers had prepared for Honolulu, Palmyra Island, Fanning Island, Jarvis Island, and Apia were made available, and it has thus been possible to identify the passage of the F-region disturbance with particular magnetic vectors (see Table 1). All times of passage have been plotted in Figure 6A and their corresponding velocities in Figure 6B. All distances are from an assumed explosion point 1½° south of Johnston Island.

TABLE 1.—A list of observation sites referred to in the text. The last column gives the nominal times of passage of the disturbance in minutes after explosion.

Station Symbol	Station	Latitude	Longitude	Time of passage (min)
	Johnston Island	16° N	170° W	0
a	Palmyra Island	6° N	162° W	12
b	Honolulu	21° N	158° W	13
c	Fanning Island	4° N	160° W	15
d	Jarvis Island	0°	160° W	15
e	Apia	14° S	172° W	35
f	Rarotonga	21° S	160° W	51
g	Christchurch	44° S	173° E	97
h	Campbell Island	53° S	169° E	136

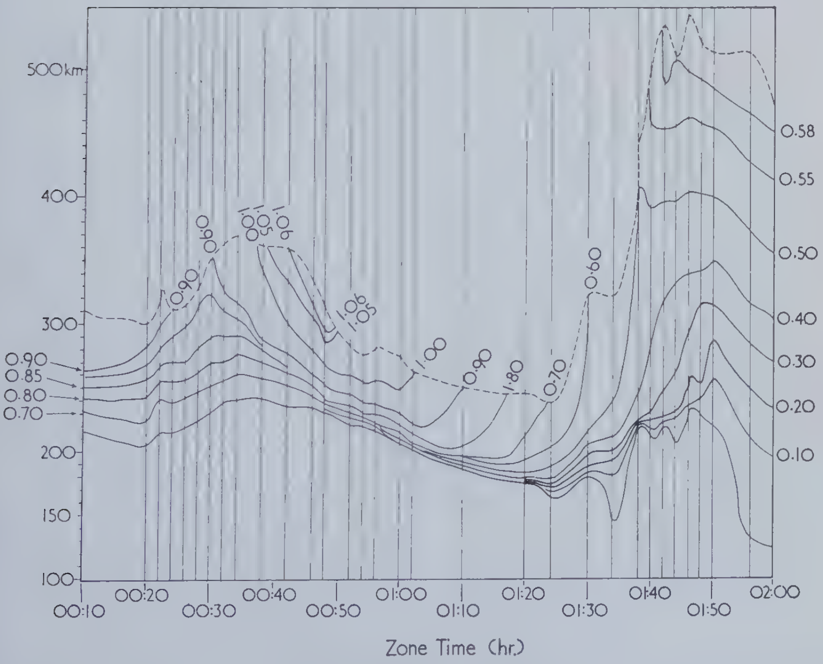

FIG. 3.—Contours of equal log f over Rarotonga, deduced by true height analysis, for the second event. Records were reduced at the times indicated by vertical lines. f is related to electron density by $N = 1{\cdot}24 \times 10^4 f^2$. The bomb was exploded at $23^h\,30^m$ on 11 August 1958.

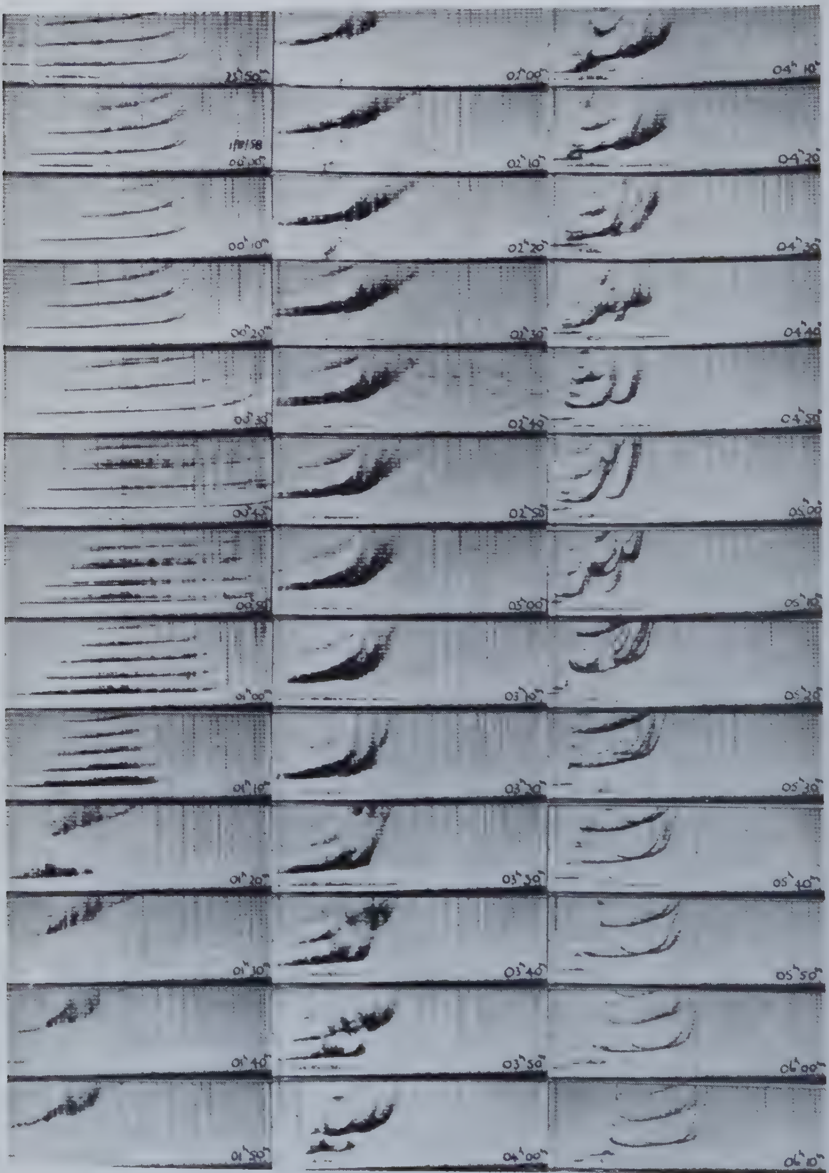

FIG. 4.—h'f records from Rarotonga during the first event. The explosion was on 31 July 1958 at 23h 50m local time.

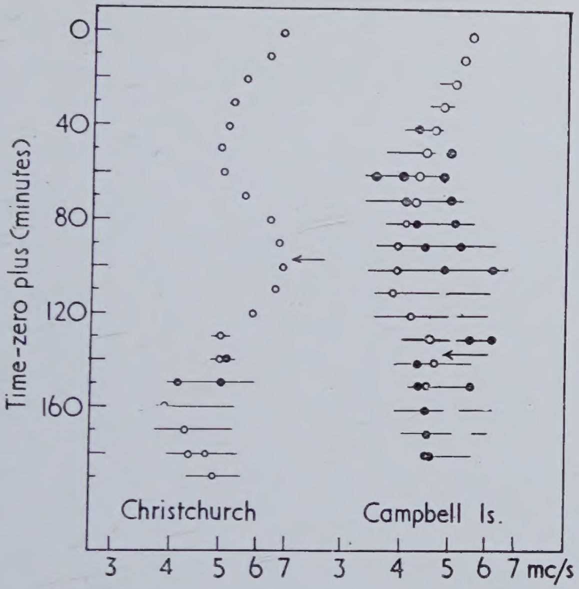

FIG. 5.—F-plot for Christchurch and Campbell Island during the first event.

INTERPRETATION OF OBSERVATIONS

The fact that a smooth curve can be drawn through the observation points (Fig. 6) suggests strongly that the velocity of propagation does not depend on radial direction and is primarily unaffected by the earth's magnetic field. Further support for this view is given by the f-plot for Adak which shows an F-region disturbance at roughly the right time. Adak is north of Johnston Island and propagation is through regions of increasing angle of magnetic dip.

One observational point, Jarvis Island (Fig. 6, d) is considerably away from the curve. As its direction lies between those of Palmyra Island and Rarotonga, the mechanism for generating its magnetic vector must be somewhat different from that at the other stations. This magnetic station is on the dip equator and it seems that the ionization in the F-region is displaced horizontally before the arrival of the main disturbance, thus advancing the time of movement of its magnetic vector. From the same cause, the time at Fanning Island is advanced by about one minute.

On Figure 6 are also shown the velocities of sound at various heights in the atmosphere, based on an atmospheric model consistent with satellite measurements. The observed propagation velocity exceeds the velocity of sound at all levels for points closer to the source than Christchurch. The observed manifestations appear to be consistent with a supersonic gaseous wave whose height of travel does not exceed 560 km.

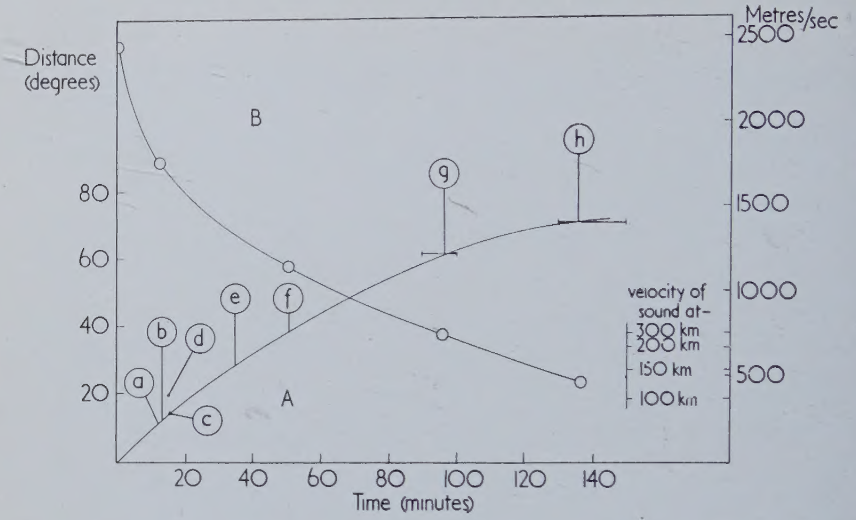

FIG. 6A.—Curve of delay times versus distance in degrees. For list of stations see Table 1.

B.—Deduced velocity curve.

The following mechanisms do not supply a satisfactory explanation:

(a) Hydro-magnetic waves.—The velocity of a classical hydro-magnetic wave is given by $V^2 = H/4\pi\rho$ along the field, and this is greater by some orders of magnitude than the observed velocity. It is interesting that no wave of this velocity was recorded, although it may have passed between records. If it occurred, its amplitude would have been very small.

(b) Electro-static waves.—One form of electro-static wave, positive ion oscillation, travels at roughly the right velocity between Johnston Island and Rarotonga. However, the velocity at Campbell Island is much below the electro-static velocity. Moreover, the fractional ionization above Rarotonga is small (of the order of 10^{-3} or less) and this form of wave would be converted rapidly into a neutral gaseous wave.

(c) Photo-ionization.—It is highly improbable that photo-ionization, with subsequent transport from the magnetic conjugate point of Rarotonga could provide an explanation; the travel time is too long. Ionization at Christchurch and Campbell Island cannot be produced in this way, because of the geometry.

CAUSE OF THE HIGH IONIZATION AT RAROTONGA

It is considered that the gaseous wave has the character of a supersonic shock wave in the lower parts of the ionosphere, and that on its upper boundary, expansion, gravitational forces, and the curvature of the earth's surface combine to produce high compression ratios which cause ionization by collision. It is to be noted that, at the F-region level, all the gas between Johnston Island and Rarotonga, if collected together, would provide a compression ratio of only 2 over the extent of the observed disturbance; gas contributed by the bomb does not affect this augment. Therefore there must be movement of gas from the more dense regions below.

The disturbance velocity at Rarotonga is not great enough to give the compression ratios required for ionization by collision, and the same applies *a fortiori* at Christchurch and Campbell Island; in fact, at Campbell Island the velocity is below the velocity of sound at the F-region level. In other words, the main disturbance travels well below the F-region and only the upper boundary where the compression ratio is anomalous can be observed by ionospheric means.

The following methods of producing high ionization densities are rejected for the reasons given:

(a) Neutron Decay.—The fire-ball from the explosion is contained by atmospheric gas and magnetic pressure and, at the time of break away of the shock front, its diameter is unlikely to be greater than 30 km. At this time, all fast neutrons have left the fire-ball and slow neutrons are still contained in it, so that the shock front will not hold many neutrons and their decay could not generate the observed ionization.

(b) Collection of Ionization by Shock Front.—There is insufficient ionization initially between Johnston Island and Rarotonga to provide the total observed at Rarotonga, and therefore, for a collection mechanism to provide sufficient ionization, considerable additional ionization would have to be produced by photo-ionization from the bomb. Trapped ionization would have to be moved across the earth's magnetic field, and for this to happen the gas pressure must exceed the magnetic pressure. This is conceivable in the lower part of the disturbance, but is impossible at the 370 km level, where the maximum ionization occurs, because it would require a disturbance velocity of Mach 4.

ACKNOWLEDGEMENTS

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